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Representing the Sea Floor with the Bathymetry Generation Model (BaGM)

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14. ABSTRACT

The Bathymetry Generation Model (BaGM) produces high-resolution representations of bathymetry for regions where the dominant sea floor material is sand. A wide variety of sand waves/ripples having either symmetric or asymmetric profiles can be represented, with many specific features that can be represented singly or in combination. Bedform length scales are virtually unlimited, ranging from a few centimeters to thousands of meters. The primary limitations are computer time/space considerations and grid size. The model is organized into modules for ease of use. The model equation has two forms, one for representing bathymetry profiles along a single line of sight and one for representing bathymetric fields, or patches of the sea floor. Although other models and methods that can be used to represent the sea floor exist, BaGM is unique in its flexibility, utility, and variety of sea floor patterns and combinations available. In the examples described in this report, the modules are utilized with an acoustic propagation model to mimic sonar performance.

15. SUBJECT TERMS

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EXECUTIVE SUMMARY

The success of many naval operations rests on the ability to quickly locate and identify possible threats from a safe standoff distance. This chore is complicated by environmental clutter that may mask or mimic target signatures. Of the many sources of clutter, bathymetry is one of the most stable. Consequently, characterization of bathymetric clutter leading to increased probability of detection may be possible. This report describes a model, the Bathymetry Generation Model (BaGM), for producing high-resolution representations of bathymetry for regions where the dominant sea floor material is sand. A wide variety of sand waves having either symmetric or asymmetric profiles can be represented. Sea floor sections consisting of specific features such as long-, short-, intermediate-crested sand waves, wavy, long-crested sand waves, or random sand waves or various combinations of features can be constructed. Bedform length scales are virtually unlimited, ranging from a few centimeters to thousands of meters. The primary limitations are computer time/space considerations and grid size. The model is organized into modules for ease of use. In the examples described in this report, the modules are used with an acoustic propagation model to mimic sonar performance. However, the bathymetry model has many other applications.

Although other models and methods that can be used to represent the sea floor exist, none were found that could produce the desired patterns or features on the needed scales. Consequently, a new model or method of producing the sea floor features was needed. The first stage of the model development started with identifying an equation capable of producing at least some of the desired properties. Subsequent modifications to the equation, program format and data handling capabilities as well as output format requirements led to the current model with three distinct modules optimized for different purposes.

Modeling a region of the sea floor starts with a description of the predominant bathymetric features and sea floor materials in the region. The sea floor parameters, including sand wave length, maximum height, symmetry, and orientation with respect to the observation direction are entered into an input data file that is then read by the model. The parameters form the input, or the basis for input, into the equation that calculates the sand wave height for each grid point. The result is, depending on the module used, a data file or set of files containing the sand wave height for each grid point defined on the sea floor region.

REPRESENTING THE SEA FLOOR WITH THE BATHYMETRY GENERATION MODEL (BaGM)

1. OVERVIEW

The bathymetry generation model described in this report evolved out of the High Resolution Mine Countermeasures (MCM): Acoustic Clutter Characterization Task at the Naval Research Laboratory (NRL). The overall goal of the task was to characterize the sources and signatures of acoustic clutter, the noise that interferes with the ability of naval sonars to consistently locate and identify objects in the ocean volume or resting on the sea floor. Clutter comes from many environmental factors, including bathymetric features, wrecks, the sea surface, bubbles, and fish. Understanding how the environment and bathymetry influence acoustic clutter can improve the chances of correctly identifying target signatures. Some environmental parameters, such as sound speed profiles, sea surface waves, fish, and bubbles, have large random components. Although it is possible to model or measure their effects, the combined random interaction makes predicting their behavior in the "real" situation impossible. Bathymetric features, on the other hand, are not only easy to observe but relatively stable over hours of time except under storm or high current conditions. Therefore, it is possible to model the sea floor to gain insights into the effects of bathymetry on acoustic reverberation and clutter and subsequent target detection. However, an essential requirement is a sea floor model capable of producing reasonable approximations to the actual sea floor, from which scattering estimates can be made. The Bathymetry Generation Model (BaGM) is designed to meet this need.

Sonar operations, both MCM and otherwise, are frequently carried out on the continental shelves and coastal regions. These areas often have large, sandy patches, the bathymetry of which may be influenced by many factors including waves, ocean or tidal currents, and bioturbation. Symmetrically profiled sand waves and sand ripples are due to sea surface waves or symmetric tidal currents, though the sand wave profiles are very different between the two formation mechanisms. Nonuniform flow due to tidal or ocean currents produces asymmetric sand waves with the steeper (lee) slope facing in the direction of maximum flow (Fig. 1). Asymmetric sand waves also tend to occur in regions where currents are combined with wave action. Mobile sand waves, important because they may partially or wholly bury objects resting on the sea floor, are generally asymmetric.

1.1 Survey of Other Models

An acceptable sea floor model must allow user selection of sand wave parameters, including those governing the sand wave profile. It must be applicable over a wide range of resolutions or grid sizes, in regions ranging from a few meters to a few kilometers and larger, and capable of producing a wide range of sea floor patterns, including asymmetric sand waves. Since small changes in the location of the sonar with respect to the sea floor/sand wave field can affect the reverberation returns, the model must be flexible and user friendly. At this point, the physical processes that produce the sand waves are not the issue (in fact, similar sand wave profiles can be produced by very dissimilar processes); only the sand wave profiles and the ability to produce them easily are needed.

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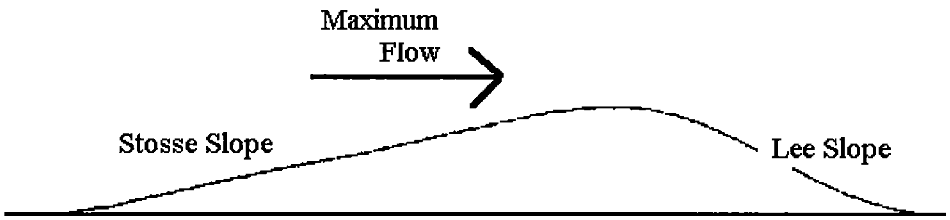


Fig. 1– Sample asymmetric sand wave profile

A literature search for bathymetry models revealed several sand wave/ripple models and theories that link various formation mechanisms to sand wave shapes. These can be divided into four general classes: sand wave formation mechanisms (primarily tidal-current models); small-scale/micro ripple models; large-scale (sea mount) features/ocean depth models; and internal structure models. Nearly all of the models have some aspects that are either of use now or may be of use in a future enhancement of the bathymetry model

At present, the latter two model types do not suit the purposes of this program. Bathymetric internal structure is important only at frequencies and/or with materials where absorption occurs. As BaGM is extended to include more penetrable materials, such as mud and silt, these models will become increasingly important. Some models of internal structure do provide useful information concerning surface sediment distribution, so they cannot be ignored. Large-scale features are unlikely in harbors and near-shore environments, where most mine hunting is done. However, they are likely to be a factor in submarine hunting, so their representation in BaGM may be considered later.

Of the remaining classes of models, those producing small-scale and micro-roughness of the sea floor are generally not used for sonar predictions. These features consist primarily of small, wave-generated sand ripples that are often lost in modeled sea floors because of the grid size required to represent a large region. Small-scale features and micro-roughness of the sea floor definitely contribute to noise in the returned sonar signal; however, their effects must be included statistically, and as yet their statistical characteristics are not well known.

Most of the models that ultimately produce sand wave patterns or profiles start from the formation mechanism, tracing the stages to a stable sand wave pattern for the given conditions. However, the present purpose of BaGM is to produce multiple model sea floors quickly. Tracing the sea floor pattern generation through the formation mechanisms is time consuming. Consequently, inclusion of formation mechanisms is left as a future extension. At this time, formation models, though important, apply to BaGM only in that comparisons between their modeled sand wave patterns and profiles and those produced by BaGM either support BaGM or point out a weakness in the model.

Models that apply to this study are briefly discussed below. All of these models have useful features, but none of them fully meet the needed specifications.

1.1.1 Wave-generated Sand Waves and Ripples

Blondeaux [1] and Vittori and Blondeaux [2, 3] developed a theory of the formation of rolling-grain and vortex sand ripples under the influence of surface or gravity waves. The model successfully produced

sand ripple patterns consistent with observations of wave-generated sand ripples. The ultimate conclusion was a theory for the formation of brick pattern sand ripples. The resultant pattern from this theory agrees reasonably with observations. Although this theory produces predictions of sand ripple patterns under various conditions, it is not intended to be a general model of the sea floor. It may be possible to use some of the theory's predicted sea floors in limited cases for acoustic modeling of sonar performance, however it is unsuitable for use in ray trace acoustic models due to the grid density required to represent the bathymetry. Furthermore, this model is limited to small sand ripples.

This theory may become more applicable as the bathymetry model is extended into the dynamic realm of mobile sand waves. Also, two very important observations are reported: (1) wave and sediment characteristics influence the type of sand ripple that forms, which suggests that not all ripple types may appear in all sediments; and (2) larger grained materials form longer wavelength sand ripples for given characteristics of the wave [1].

Other sand ripple and sand wave models have been developed since BaGM was first developed and this report was originally written. As with the models described above, they generally link a formation method to the ripple patterns and are not suitable nor intended for use with acoustic models. Therefore, they are not discussed in this forum.

1.1.2 Tide-generated Sand Waves and Ripples

Allen's [4] model for tidal sand waves produces experimentally verified one-dimensional sand wave profiles similar to those produced by the sand wave equation used in the model described in this report. If this model was easier to use, extended into the wave-generated sand wave realm, and its sand wave profile production parameters were linked to sand wave properties rather than water column properties, it would be comparable to BaGM. However, Allen's model was not designed for use with acoustic reverberation models and is awkward when used recursively. The model uses the average depth of the water, the depth of the water over the crest of a sand wave, and the angle of the slope with respect to the horizontal to generate a profile for one slope of a sand wave. The second slope of the sand wave is produced similarly. It is not possible, using this model, to use measured values from actual sand waves or the corresponding parameters to generate the profiles. The primary factor influencing the shape of the sand waves in Allen's model is water depth, requiring extensive observation and calibration to link the water depth with the shape of the sand wave slope. Furthermore, Bokuniewicz et al. [5] showed that, although water depth imposes an upper limit on sand wave height, it is not the determining factor in sand wave shape. They found, consistent with observations by Inman [6] and Langhorne [7], that the sea floor material is more important than water depth. Consequently, Allen's model's primary contribution to this study is that it verifies the correctness of the sand wave equation profiles into the tide-generated sand wave regime.

1.1.3 dbSEABED

A program called dbSEABED [8] scans observational data sets for information concerning seabed roughness. This method is intended to be a way to provide bathymetric, sea floor material, and seabed roughness data to acoustic propagation and backscatter models as well as sediment transport and shallow-water wave dissipation models. Depending on the availability of data and the type of information needed, in some regions, this model may be superior to BaGM.

The major strength of dbSEABED is that it works by collecting data from actual observations from sea floor databases. The types of information include: sizes and abundances of outsized objects (clasts, shells, boulders); observations of ripples and sand ridges; evidences of bioturbation; and reports of blocks, crevasses, fissures, depressions, and potholes. dbSEABED cannot, however, represent roughness elements on scales larger than the observational footprint. Consequently, features such as sand ridges, outcrops,

pinnacles and reefs should be obtained from bathymetric surveys or other means. Since the model works off observations, its usefulness in areas where observations are scarce or not possible is limited.

Although dbSEABED has the potential to be superior to BaGM in specific areas, from the information provided, it appears that it cannot be used to compare the effects of different types of sand waves on acoustic signals or wave/seabed interactions. In other words, the use of dbSEABED requires that two conditions be met: (a) there is a specific location about which seabed roughness information is needed and (b) there is data for that region in the databases used with dbSEABED. BaGM, on the other hand, can be used to compare the effects of "generic" regions on the acoustic signal and can be used to construct approximate seabed roughness and bathymetry in regions where actual measurements cannot be made, based on the knowledge of tides, ocean currents, and wave/storm events. It must also be noted that at the time that BaGM was initially developed, dbSEABED did not exist.

1.2 New Model

In the final analysis, none of the bathymetry models surveyed provided all the desired properties. This led to the challenge of developing a bathymetry model that provides the needed features with meager computer resources. An equation that represents sand wave profiles and the effects of varying input parameters is presented in Section 2. The equation links sand wave height to position on the sea floor. The required input parameters are either sand wave or sea floor feature observables or derived from the observables.

This sand wave profile equation is the heart of BaGM, a static sea floor model. The sand wave equation is a serendipitous modification of an empirical sand ripple profile equation from Sleath [9] that produces realistic profiles of wave-generated symmetric, tide-generated symmetric, and asymmetric sand waves and ripples. No other equation capable of producing complete asymmetric sand wave profiles has been found in the literature.

Section 3 extends that presentation by describing three ways in which the equation, producing sand wave profiles only, can be used to model the sea floor. The equation has a one-dimensional (1D, $z = z(x)$) form and a two-dimensional (2D, $z = z(x, y)$) form, where the dimensionality of the model is defined by the number of independent degrees of freedom in the sand wave equation. In each case, the sand wave height, z, is dependent on the location, (x, y). BaGM uses these two forms of the equation to represent sea floor bathymetry arising from a variety of environmental conditions. It currently has three modules; two use the 1D version and one uses the 2D version of the sand wave equation. BaGM produces symmetric and asymmetric sand waves and ripples for multiple bedform patterns. It is also possible to model composite bedforms including multiple overlying sand wave patterns.

Since the equation is analytical, in theory the sea floor represented can be of any size, with grid point spacing ranging from very small to very large. In practice, the physical dimensions of the sea floor patch that can be represented depend on the step size selected and the maximum size of the data file. The various modules allow sea floor representations ranging from finely detailed two-dimensional ($z(x, y)$) representations of a small patch to more coarse sand wave profiles along a single radial spanning several kilometers. To date, the smallest step size used in the two-dimensional version is 0.18 cm, representing features having sand wavelengths as small as 7 cm, in a region 2.5 m by 5.0 m. The largest region represented using a one-dimensional module had radials 3 kilometers long, with a radial fan of 60°. The step size was 1.26 m, representing sand wavelengths between 7.5 and 1000 m. These sand wavelengths and grid sizes are merely representative of the range of possibilities of this model, not its limits. Module choice is user-determined based on the desired use of the sea floor representation and bathymetry data file format requirements. As an example, these model sea floors can be used to give insights into the effects of bathymetry and changes in the bathymetry on acoustic reverberation and clutter.

2. THE SAND WAVE EQUATION

2.1 Equation Development

The core of any bathymetry model is the equation(s) or set of data files providing the sea floor height vs position information. The better the representation of the actual sea floor, the more likely it is that the acoustic reverberation model will produce valid results. The first step of the model development was a search for a way to represent the sea floor easily, preferably an equation or set of equations that had been or could be shown to accurately trace observed sand wave profiles. In the case of symmetric, wave-generated sand ripples, such an equation was found in Sleath [9] (Chapter 4, Eq. 2.22). That equation, linking height above or below mean sea floor to range, has been shown to accurately reproduce wave-generated symmetric sand ripple profiles. It is the $\eta = 0$ reduction of the explicit, curvilinear coordinate, analytical solution [9] (Chapter 2, Eq. 2.21) for oscillatory flow over a rippled bed

$$\eta = z - \frac{h}{2}e^{-k\eta}\left(1 + \cos k\xi\right) \tag{1a}$$

$$\xi = x + \frac{h}{2}e^{-k\eta}\sin k\xi \tag{1b}$$

In these equations, h is the sand wave amplitude, k is the wave number, x is the range, and z is the sand wave height. The first generation form of our bathymetry model used a first order approximation of the $\eta = 0$ Sleath equation with an adjustment to make the minimum sand wave height equal to zero

$$z = \frac{h}{2}\left[1 + \cos\frac{2\pi}{\lambda}\left(x + \frac{h}{2}\sin\frac{2\pi}{\lambda}x\right)\right] \tag{2}$$

where k is replaced by its equivalent expression, $\frac{2\pi}{\lambda}$, $\lambda \equiv$ sand wavelength. Using amplitude modulation, this bathymetry generation model can produce three of the wave-generated sand wave patterns described in the literature [6]: short-, intermediate-, and long-crested. Another sand wave pattern, random ripples/waves, is generated by adding sets of scaled, long-crested sand waves having randomly selected orientations with respect to the observation direction. Appendix A defines the sand wave types. It is assumed for modeling purposes that the larger bedforms, mega-ripples, sand waves, and sand dunes, formed by the same processes may be taken to be larger versions of sand ripples.

Although the first generation model successfully produced both simple and composite bedforms with symmetric sand wave profiles using the simplified Sleath equation, this is not sufficient for modeling all pertinent bedforms. No bedforms with asymmetric sand wave profiles could be produced. Yet no equation for generating asymmetric sand ripple/wave profiles has been found in the literature. At present, the asymmetric sand wave profiles are generally taken from data files that have been hand generated, based on either a "saw-tooth" pattern or recursively entered measured sand wave profiles. Although these methods are perfectly reasonable, they are tedious and do not allow a great deal of variability in the shape of the sand wave/ripple. Therefore, finding an alternate method of generating asymmetric sand wave profiles was a priority. The remainder of this section describes such a method, its limitations and use.

2.1.1 1D Sand Wave Equation

In this and the first-generation bathymetry models, there are two simple ways to vary the starting point on the sand wave/bathymetry. The first is to generate the sea floor, then shift the zero range point to some height point other than the first one generated. The problem with this method is that the changes in position are governed by the step size used to generate the bathymetry. The second method is to apply a phase shift

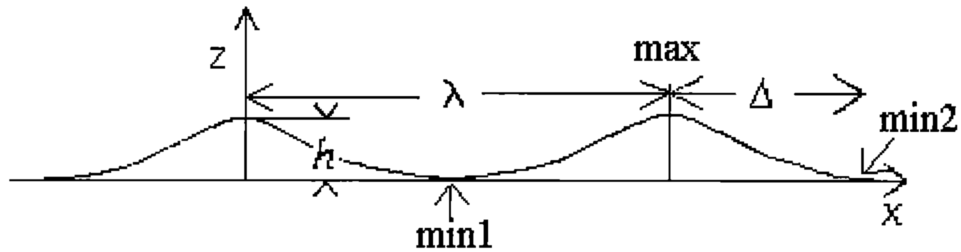


Fig. 2– Definition of terms. The designations of min1, min2, and max refer to Table 1. Δ is the crest-to-trough length connected to the symmetry parameter, β, as defined in Eq. (5).

to the starting point so that the zero point range is not the sand wave equation zero point. The discovery of an equation that produces acceptable asymmetric sand wave profiles was a serendipitous side effect of the effort to introduce a random starting point (phase shift) into the original sand wave equation. The new equation can be expressed in two equivalent ways,

$$z = C\frac{h}{2}\cos\left\{\frac{2\pi}{\lambda}\left(x' + \frac{h}{2}\sin\frac{2\pi}{\lambda}x'\right) + \phi\right\} \tag{3a}$$

$$z = C\frac{h}{2}\left[1 + \cos\left\{\frac{2\pi}{\lambda}\left(x' + \frac{h}{2}\sin\frac{2\pi}{\lambda}x'\right) + \phi\right\}\right], \tag{3b}$$

where $x' = x+\delta$ and z is the height of sea floor, x is the range, ϕ is the phase factor, such that $(0 \leq \phi \leq 2\pi)$, λ is the sand wavelength (spacing between successive crests or troughs), h is the sand wave crest amplitude, and C is the scale factor, with $(0 < C \leq 1)$. Figure 2 gives graphic definitions of the measurable parameters z, x, λ, and h. The parameter δ $(0 \leq \delta \leq \lambda)$ is a randomly selected starting point for the sand waves in the sand wave field. The phase factor ϕ determines the symmetry β of the sand wave profile. The symmetry parameter β is calculated from observed values and related to ϕ through sets of fourth order equations (discussed later in this section). The scale factor C, generally set equal to one, scales the sand wave height to allow more asymmetric profiles in sand waves having small height-to-length ratios $\eta = \frac{h}{\lambda}$[1].

These equations differ from the one in the first order bathymetry model only in the addition of the phase shift ϕ to the argument of the cosine, the scale factor C and the use of x' in place of x. It is the addition of ϕ to the equation that makes it possible to produce asymmetric sand wave profiles. Sand wave heights generated using Eq. (3a) range from $-\frac{h}{2} \rightarrow +\frac{h}{2}$. Equation (3b) contains an adjustment to make the minimum value of "z" equal to zero (sand wave heights range from $0 \rightarrow h$) to accommodate acoustic model constraints. Sand wave equation properties and the available sand wave crest patterns are unchanged.

2.1.1.1 The Purpose of δ

Suppose that you wish to model acoustic reverberation from a sand wave field having some known η and β. The sonar location is some place in this field, defined as range, $x = 0$. This places the sonar location directly above some point on one of the sand waves and determines the distance between the sonar and each sand wave crest. For a given choice of ϕ, this point is predetermined.

In the real world, there can be significant variations between reverberation returns of successive sonar pulses along a single path. These arise from oscillations in the sonar depression angle with surface waves,

[1] η used in Eq.(1) is a curvilinear coordinate and not to be confused with η, the sand wave height-to-length ratio, used in the balance of this report.

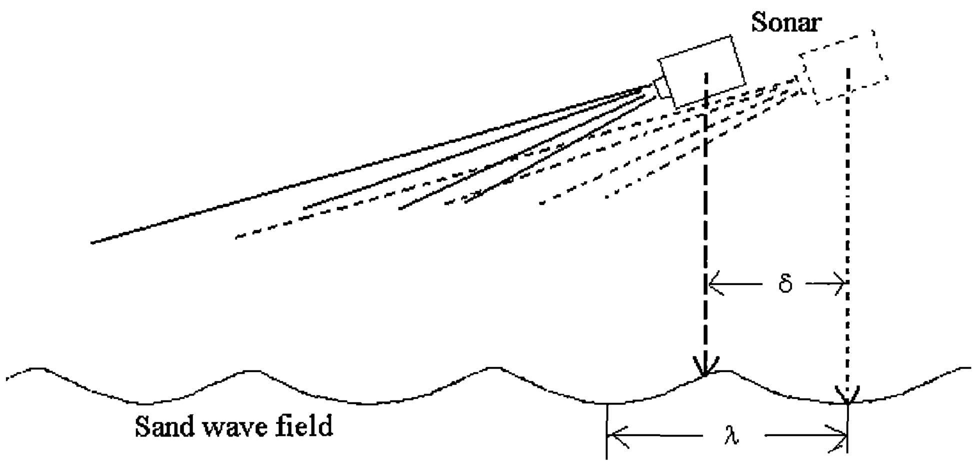


Fig. 3– An example of the shifting in the position of the sonar with respect to the sand wave field using the factor δ

changes in sonar height above the sea floor with tides and swell, and random variations in the water column properties due to a wide variety of environmental factors.

In the modeled world, however, these random variations do not occur. Consequently, successive reverberation calculations produce exactly the same results. Hence, the addition of the factor δ, a range position between zero and λ. It is usually randomly generated for each bedform in each set of sonar observation paths, though it can be user determined. Applying δ moves the "location" of the sonar with respect to the first sand wave, as shown in Fig. 3. This changes the angles and locations that the rays representing the sonar pulse impact the sea floor. This slight change in the "sonar location" in the model mimics the random changes in sonar position in the real situation. When multiple reverberation model runs on bathymetry varied only by different δ's are averaged or statistically combined in the final analysis, the approximation to the real world is improved as compared to any single run.

The variable δ also applies when sea floors of multiple overlying bedforms are constructed. Since Eq. (3) is a scaled cosine function, when the ϕ's of the different bedforms are the same, the zero range or sonar position would occur at exactly the same relative positions on all bedform profiles. It is unlikely that this would occur in a real situation, but without the inclusion of the different δ's for each bedform in the profile equation, that is exactly the case.

2.1 2 2D Sand Wave Equation

The 1D sand wave equation can be extended to two dimensions for more detailed representation of the sea floor. The resultant equation is in a left-handed coordinate system rather than the usual right-handed coordinate system. This is due to the way the parameters are defined in the original equation; the observation direction is defined along the x-coordinate. All parameters in the 2D equation are defined as in the 1D equation, with the addition of the orientation angle θ of the sand wave crests with respect to the observation direction (Fig. 4). Also, x' is replaced with the quantity $x\cos\theta - y\sin\theta$ to include the orientation information of the sand wave crests with respect to the observation direction. The resultant 2D form of the sand wave equation is, for sand wave heights ranging from $0 \rightarrow h$,

$$z = C\frac{h}{2}\left\{1+\cos\left[\frac{2\pi}{\lambda}\left(x\cos\theta - y\sin\theta\right) + h\frac{\pi}{\lambda}\sin\left[\frac{2\pi}{\lambda}\left(x\cos\theta - y\sin\theta\right)\right] + \phi\right]\right\} \tag{4}$$

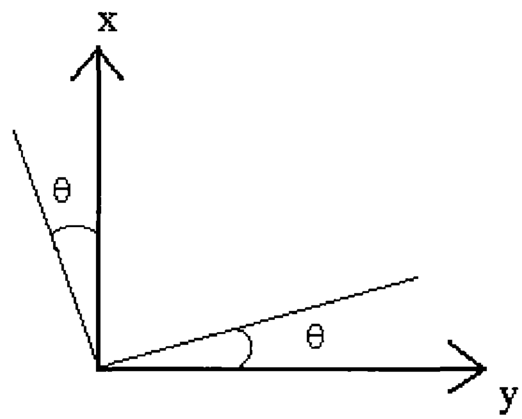


Fig. 4– Coordinate system for the 2D sand wave equation; x defines the observation direction and θ is the angle that the perpendicular to the sand wave crest makes with the observation direction. The coordinate system is left-handed.

Removing the "1 +" from Eq. (4) makes it analogous to Eq. (3a), with sand wave heights ranging from $-\frac{h}{2} \rightarrow +\frac{h}{2}$.

2.2 Sand Wave Equation Properties

The following discussion concentrates on the 1D form of the equation; however, it also applies to the 2D form.

The power of Eqs. (3) and (4) is their ability to produce both symmetric and asymmetric sand wave profiles. The equations retain their cyclic nature with respect to range, such that $z(x_o + n\lambda,\ n = 1, 2, 3, ...) = z(x_o)$. This simplifies the generation of bathymetries consisting of fields of sand waves over a large region. However, it is also possible to break the cyclic nature of the equations by making the phase factor range dependent.

The location of the first minimum on a modeled sand wave is determined by η and ϕ. However, it may be desirable to shift this value, for example, to generate multiple versions of sand waves having the same parameters. The factor δ is used to change the location of the first minimum of the sand wave. This may be done randomly or deliberately without changing the sand wave profile as long as the shift is included in the value of x, such as $x \rightarrow x + \delta$ (as in the equation as presented) where δ obeys the relation $0 \leq \delta \leq \lambda$.

The shape of the sand wave profile is governed by ϕ and, to a lesser extent, η. The orientation (whether the lee slope faces toward or away from the observer) is governed by ϕ. When ϕ is near zero or 2π, the sand wave profile equation defaults to the original equation, producing symmetric, wave-generated type sand wave profiles. Symmetric sand wave profiles such as those due to symmetric tidal flows are produced when $\phi \sim \pi$. Asymmetric sand wave profiles are generated for all other ϕ, although the profiles are approximately mirror images when they differ from π by plus or minus the same angle. The most asymmetric profiles for any η are produced at $\phi \sim \frac{n\pi}{2}$, $n = 1$ or 3. The shift in profile shape is cyclic in ϕ, repeating itself every 2π. Figure 5 shows the progression in the sand wave profiles as ϕ varies through a range of 0 to $\frac{3\pi}{2}$. The displayed sand waves have a wave length of 10.0 m, and a wave height of 1.5 m ($\eta = 0.15$).

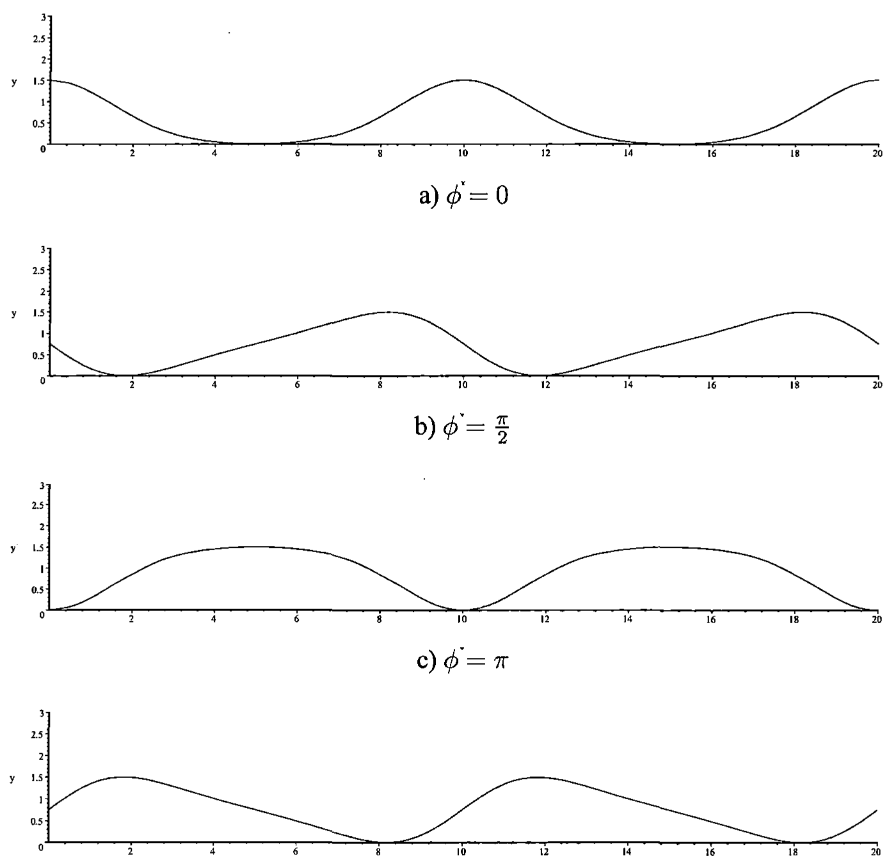
If the sand wavelength and wave amplitude are selected to keep η constant, then the sand wave profile is unchanged as long as the same ϕ is chosen. As a result, the equation can be easily calibrated with ϕ and η linked to the sand wave profile. This equation and its current modifications are more flexible and cover

a much wider spectrum of sand wave profiles than any other sand wave profile generating method we have found, although they do not allow representation of the more extremely asymmetric sand wave profiles.

The symmetry parameter β for a sand wave is the ratio of the crest-to-trough distance Δ (Fig. 2), and the wavelength

$$\beta = \frac{\Delta}{\lambda}. \tag{5}$$

The parameter β (or $1/\beta$) is important because it is a simple way to characterize the sand wave and easily calculated from measured sand wave attributes. In the case of the sand wave equation, the observables are related to the equation results through the following relationships: min2$-$ max $\equiv \Delta$ and min2$-$ min1 $\equiv \lambda$, where min1, min2, and max are the wave height first and second minimums and intervening maximum. The degree of asymmetry of a sand wave is determined by how much β differs from 0.5, with the more extremely asymmetric sand waves having β's near zero or 1. The crest-to-trough distance is generally measured toward the shore. Therefore, $\beta < 0.5$ when the lee slope is toward the shore, and $\beta > 0.5$ when the lee slope is away from the shore. Thus, β not only describes the symmetry of the wave, but also indicates the direction of maximum current flow. When the lee slope is oriented at an oblique angle to the shore line, Δ is measured perpendicular to the crest line in the direction closest to the shore. Table 1 tabulates β and the location of the first and second minimums and the first maximum in sand wave height as



a) $\phi^{*} = 0$

b) $\phi^{*} = \frac{\pi}{2}$

c) $\phi^{*} = \pi$

d) $\phi^{*} = \frac{3\pi}{2}$

Fig. 5– Effect of phase factor on sand wave shape and position for sand wave with $\eta = 0.15$. Vertical and horizontal axes are scaled equally; actual values are relative.

Table 1– Positions of the First and Second Minimum, First Maximum, and the Symmetry Parameter vs Sand Wave Height-to-length Ratio for $\phi = \frac{\pi}{2}$

η	min1	max	min2	β
0.05	2.25	7.75	12.25	0.45
0.075	2.13	7.87	12.13	0.43
0.10	2.02	7.98	12.02	0.40
0.15	1.82	8.18	11.82	0.36
0.175	1.73	8.27	11.73	0.35
0.20	1.61	8.36	11.66	0.33

η changes[2]. The last column indicates that the most asymmetric sand wave profile produced for $\eta = 0.05$ is very nearly symmetric.

The β of a sand wave does not define its shape. Often the same β is measured for very different sand wave profiles. The symmetry parameters of the sand wave profiles produced by Eq. (3) are essentially symmetric for values of ϕ near $\frac{\pi}{2}$ or $\frac{3\pi}{2}$, but the profile shapes are not the same. For example, the sand waves shown in Fig. 6 have the same symmetry parameter, $\beta = 0.368$, but their profiles are different and the positions of the peak and troughs are not the same.

Sand wave profiles for all ϕ are more symmetric for lower values of η. This effect is shown in Fig. 7. In this example, $\phi = \frac{\pi}{2}$, and η ranges from 0.05 to 0.20, in steps of 0.05. The sand wave profiles displayed in Fig. 7 are the most asymmetric possible from Eq. (3), with $C = 1$, for the given η's. It is important to note that in the equation, η affects the locations of the peaks and troughs of an asymmetric sand wave as well as its profile, with the overall combination producing the increase or decrease in symmetry (Table 1). This is caused by the scaling of the sine factor in the equation with the sand wave height.

When the desired symmetry parameter is outside the normal range produced by the sand wave equation, a sand wave profile with higher η and the desired symmetry parameter can be generated using the sand wave equation, with the scale factor, $C \neq 1$, making its maximum height correspond to the required η. Figure 8 demonstrates this procedure with $\eta = 0.20$ to produce the original profiles used in the scaled versions. The scale factor for adjusting Eq. (3) is found from the ratio $\frac{\eta}{\eta'}$ of the actual or desired η and the height-to-length ratio needed to get the right β, η'. For the example shown, $\frac{\eta}{\eta'} = 0.5$ and 0.25. Therefore, η's of the sand waves are scaled to 0.10 ($C = 0.5$) (thick, solid) and 0.05 ($C = 0.25$) (thin, solid), with the corresponding unscaled sand wave equation profiles shown as dashed and dot-dashed lines, respectively. The same phase factor, 90°, is used for all profiles, but only the scaled profiles have the same symmetry parameter; the unscaled profiles demonstrate the reduction in asymmetry of the profile previously mentioned. However, this technique is limited by the parameters of the sand wave equation. If the sand wave amplitude used in generating the original, unscaled profile is too great, the resultant profile, unlike real sand wave profiles, has two peaks, the second resulting from the sine term. Plotting the most asymmetric sand wave profile (corresponding to $\frac{\pi}{2}$) for increasingly higher η indicates that $\eta = 0.25$ is the practical upper limit. Therefore, the overall range of β is limited to $\beta = 0.294 \rightarrow 0.696$.

[2] The difference between the first and second minimums as shown in Table 1 is not exactly 10.0 m. This is due to the step size used in Eq. (3) to generate the output files; the sand wave length is invariant.

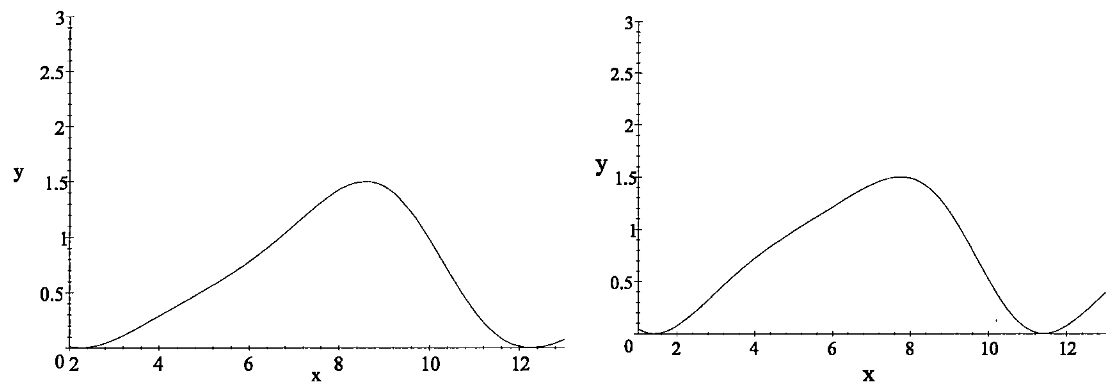


Fig. 6– The value of β does not control sand wave shape. This is an example of sand wave profiles having the same symmetry parameter, $\beta = 0.368$ and $\eta = 0.15$.

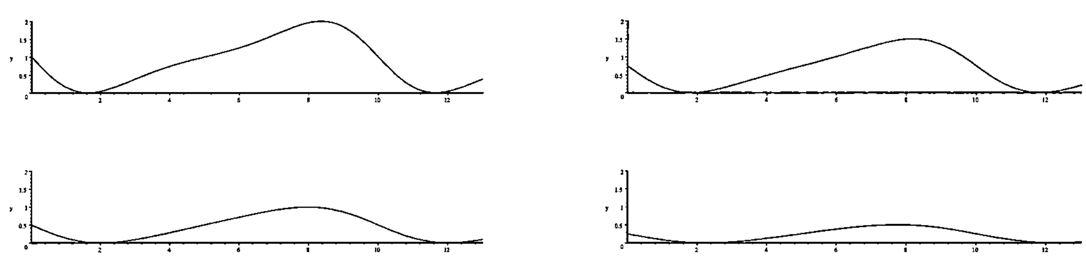


Fig. 7– The effect of varying the height-to-length ratio, η, of the sand wave. Displayed sand waves $\phi = \frac{\pi}{2}$, and η of 0.20, 0.15, 0.10, 0.05. The sand waves are plotted with height and length scales equal. Notice that waves with lower values of η are more symmetric.

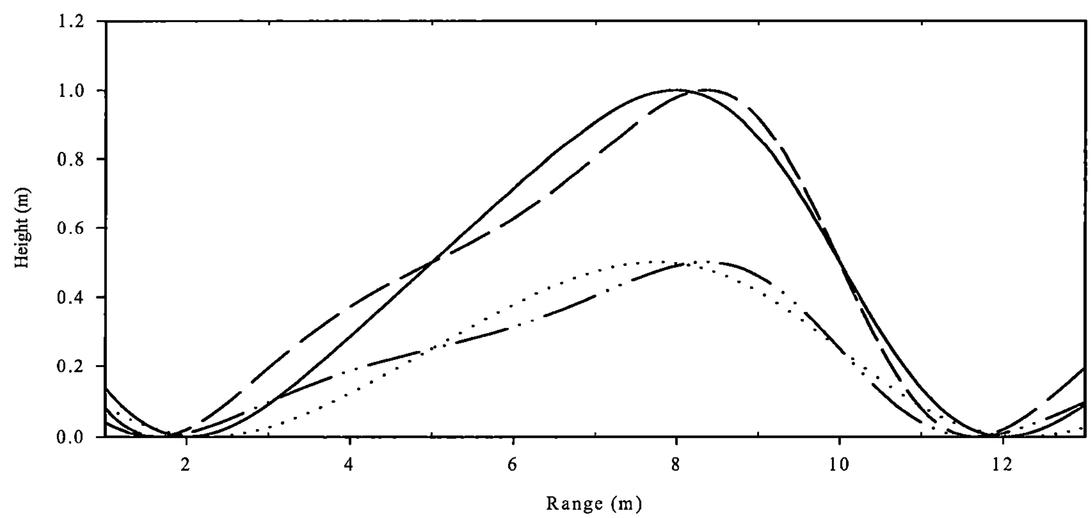


Fig. 8– Asymmetric, low η sand wave profiles created by scaling higher η sand wave profiles and the corresponding sand wave equation produced sand wave profiles. The η's of the sand waves are then scaled to 0.10 (dashed) and 0.05 (dash-dot), with the corresponding unscaled sand wave equation profiles shown as solid and dotted lines, respectively.

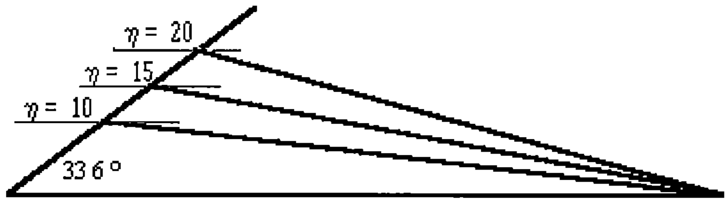


Fig. 9– Sawtooth pattern showing the greatest asymmetry allowed given the angle of repose of ground quartz

2.3 Comparison of Experiment and Theory

For sand waves in the ocean, the angle of repose[3], a_r, of the sea floor material determines the maximum allowable slope of a sand wave face. According to Nielsen [10], a_r of the sea floor material also determines the maximum height-to-length ratio through the relation

$$\eta_{\max} = \left(\frac{h}{\lambda}\right)_{\max} \approx 0.32 \tan a_r. \tag{6}$$

Using crushed quartz in water, $a_r = 33.6°$ [11], as an approximation for sand in water, the value of $\eta_{\max}$ is

$$\eta_{\max} \approx 0.32\,(\tan 33.6) = 0.21. \tag{7}$$

This is in good agreement with Inman's observations [6] of wave-generated sand ripples off the California coast, with maximum η's of 0.21 and 0.22.

The slope determined by a_r, in turn, limits the degree of asymmetry possible for a given sand wavelength and height; by combining η with a_r, an estimate of the minimum and maximum values of the symmetry parameter can be obtained. For example, suppose that Fig. 9 represents a sand wave. Since the lee slope is at a_r, this approximates the most asymmetric profile possible for any η. When $\eta = 0.10$, the corresponding $\beta = 0.15$ or 0.85 (depending on whether the lee slope is toward or away from the observer); when $\eta = 0.20$, $\beta = 0.30$ or 0.70. This demonstrates an inverse relationship between the allowed range of β and η. Observations [6, 7] support the idea that the more asymmetric bedforms have low to very low η. However, the unscaled equation demonstrates the opposite behavior, with the lower η profiles being mostly symmetric for all choices of ϕ (Table 2). This behavior led to the scaling technique previously described.

As yet, no modification to Eq. (3) can account for very asymmetric sand waves, such as those measured near the head of Wilmington Canyon on the outer Atlantic continental shelf [12]. The average sand wave height for these sand waves is approximately 4 m with inter-sand wave spacing around 350 m. The sand waves appear solitary, suggesting that the peak-to-peak spacing is greater than the sand wavelength; however, if the average sand wavelength is taken to be on the order of the inter-sand wave spacing, then η is around 0.01. This is well outside the attainable range of the sand wave equation. Sand waves with these very low η's are not uncommon, but they typically are very large, often on the same order of magnitude as

[3] The angle of repose is the maximum angle that the material makes with the horizontal when it first stops moving (where it naturally rests) This is not necessarily the angle of the lee face of a moving sand wave, since other forces are involved that may reduce the actual angle. (An unstable equilibrium condition may allow for occasional, temporary slopes having angles greater than the angle of repose.)

Table 2– Comparison of Symmetry Parameters for Asymmetric Sand Waves Based on the Sand Wave Profile Equation and Angle of Repose of Crushed Quartz

η	Unscaled Sand wave equation		$\measuredangle$ of repose	
	β (min.)	β (max.)	β (min.)	β (max.)
0.20	0.322	0.678	0.301	0.699
0.15	0.364	0.636	0.226	0.774
0.10	0.404	0.596	0.151	0.850

the observation region. This makes representing their effects through techniques other than with Eq. (3) a reasonable compromise.

Mulhearn [13] gave an example of a mobile sand wave having parameters $\eta = 0.10$, and $\beta = 0.333$ or 0.667 using a sawtooth pattern. Assuming these values to be reasonable for asymmetric sand waves, we wish to generate similar sand wave profiles using Eq. (3). Table 2 shows that these values of the symmetry parameter β for $\eta = 0.10$, are outside the attainable range of the unscaled sand wave equation. However, scaling the overall amplitude as previously described makes it possible to produce a sand wave profile with the desired parameters, as can be seen in Fig. 10. The solid asymmetric sand wave profile has $\eta = 0.10$ and $\beta = 0.333$ and was produced from the equation using the scaling technique, with $C = 0.5$ and $\eta = 0.20$. The dashed profile was produced by the unscaled sand wave equation using $C = 1$ and $\eta = 0.10$, with the same ϕ $(= 60.5°)$ and λ $(= 10 \text{ m})$. The symmetry parameter corresponding to the dashed sand wave profile is $\beta = 0.416$.

2.4 Implementation

It is relatively easy to create various bathymetries using different parameters in the sand wave equations, then compare the results with observed sand waves until a match is made. The challenge is in identifying the sand wave parameters required to reproduce the bathymetry at a specific site and time. This is because the measured sand wave parameters are generally λ, h, and Δ, from which η and β are calculated. However, Eqs. (3) and (4) generate sand wave profiles from λ, h, and ϕ. Therefore, it is necessary to connect the model input parameters with the resultant sand wave profile and asymmetry. In other words, somehow the connection between ϕ and β, for a given η, must be established.

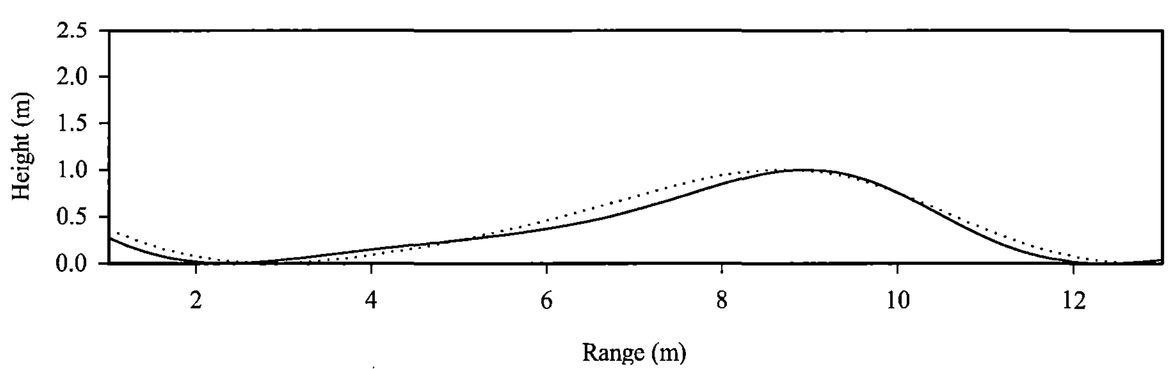


Fig. 10– A scaled sand wave profile with $\eta = 0.10$ and $\beta = 0.333$ (solid) with the unscaled sand wave equation profile for $\eta = 0.10$ and $\beta = 0.416$ (dashed)

The easiest way to establish the relation of Eqs. (3) and (4) to measured parameters and observed sand wave profiles is a two-step process using the scaling technique.

- Sand wave profiles are generated by varying ϕ for a set value of η with the corresponding β calculated from the results.
- The sand wave profile is then scaled for any value of η without affecting the relationship between β and ϕ.

Table 3 shows β calculated from the output of Eq. (3) for selected values of η and ϕ. This table can be used to estimate the values of λ, h, and ϕ needed to generate the sand wave profile corresponding to the desired β. Linearly interpolating between the values in the table gives values of β good to two significant figures.

Alternately, a set of empirical equations can be used to calculate β for a given η and ϕ, where the required values to model a specific sand wave profile are found by trial and error. Table 3 can be used to refine the estimates of η and ϕ used in the equations. The value of β for sand wave profiles produced by Eq. (3) is represented by a fourth-order polynomial equation, with the phase shift (in meters), $\phi' = \frac{\phi(\text{rad})\lambda}{2\pi}$ or $\phi' = \frac{\phi(\text{deg.})\lambda}{360^\circ}$, given in terms of the corresponding fractional part of the sand wavelength rather than an angle:

$$\beta\left(\phi', \lambda, \eta\right) = Au^4 + Bu^3 + Du^2 + Eu + F, \tag{8}$$

where

Table 3– β vs η and ϕ

Phase Shift (degrees)	Symmetry parameter, β						Phase Shift (radians)
	$\eta = 0.21$	$\eta = 0.175$	$\eta = 0.15$	$\eta = 0.10$	$\eta = 0.075$	$\eta = 0.05$	
0	0.500	0.500	0.500	0.500	0.500	0.500	0
18	0.406	0.429	0.440	0.466	0.476	0.484	$\frac{\pi}{10}$
36	0.361	0.386	0.405	0.439	0.455	0.470	$\frac{\pi}{5}$
54	0.337	0.362	0.380	0.420	0.440	0.460	$\frac{3\pi}{10}$
72	0.326	0.350	0.368	0.408	0.430	0.453	$\frac{2\pi}{5}$
90	0.322	0.346	0.364	0.404	0.426	0.450	$\frac{\pi}{2}$
108	0.325	0.350	0.368	0.408	0.430	0.453	$\frac{3\pi}{5}$
126	0.337	0.362	0.380	0.420	0.440	0.460	$\frac{7\pi}{10}$
144	0.361	0.386	0.405	0.439	0.455	0.470	$\frac{4\pi}{5}$
162	0.406	0.429	0.444	0.466	0.476	0.484	$\frac{9\pi}{10}$
180	0.500	0.500	0.500	0.500	0.500	0.500	π
198	0.594	0.571	0.556	0.534	0.524	0.516	$\frac{11\pi}{10}$
216	0.639	0.614	0.595	0.561	0.545	0.530	$\frac{6\pi}{5}$
234	0.663	0.638	0.620	0.580	0.560	0.540	$\frac{13\pi}{10}$
252	0.674	0.650	0.632	0.592	0.570	0.547	$\frac{7\pi}{5}$
270	0.678	0.654	0.636	0.596	0.574	0.550	$\frac{3\pi}{2}$
288	0.674	0.650	0.632	0.592	0.570	0.547	$\frac{8\pi}{5}$
306	0.663	0.638	0.620	0.580	0.560	0.540	$\frac{17\pi}{10}$
324	0.639	0.614	0.595	0.561	0.545	0.530	$\frac{9\pi}{5}$
342	0.594	0.571	0.556	0.534	0.524	0.516	$\frac{19\pi}{10}$

$$u = \begin{cases} \phi' - \left(\frac{\lambda}{4}\right) & \text{for } \phi' \leq \frac{\lambda}{2} \\ \phi' - \left(\frac{3\lambda}{4}\right) & \text{for } \phi' \geq \frac{\lambda}{2}. \end{cases}$$

The coefficients of the polynomial, A, B, D, E, and F, depend on η and whether ϕ' is less than or greater than $\frac{\lambda}{2}$. One set of coefficient equations governs the behavior of the sand wave when the $\phi' < \frac{\lambda}{2}$ ($\phi \leq \pi$), the other gives the coefficients when $\phi' > \frac{\lambda}{2}$ ($\pi \leq \phi \leq 2\pi$). Both sets of equations work for $\phi' = \frac{\lambda}{2}$. The equation for β and those for its coefficients were found using the MATLAB polynomial fitting routine, POLYFIT[4], on digitized sand wave profiles.

The coefficients of Eq. (8) in the case of $\phi' \leq \frac{\lambda}{2}$ may be found from the following set of equations:

$$A = -0.0449\eta^3 + 0.1642\eta^2 - 0.0201\eta + 0.0004 \tag{9a}$$
$$B = 0.0000 \tag{9b}$$
$$D = 8.8335\eta^4 - 5.5783\eta^3 + 0.0508\eta^2 + 0.1961\eta \tag{9c}$$
$$E = 0.0000 \tag{9d}$$
$$F = 1.12511\eta^2 - 1.1185\eta + 0.5034 \tag{9e}$$

For the most part, these equations do a very good job of representing the coefficients, except for the coefficient for the u^2 term, which fits very well at the upper and lower ends of η spectrum, but less well in the mid-range.

The coefficient equations for the case of $\phi' \geq \frac{\lambda}{2}$ do not represent the coefficients as well as those (Eqs. (9)) for $\phi' \leq \frac{\lambda}{2}$. However, β's calculated from these coefficients should be valid to within two significant figures. The equations are:

$$A = -0.3022\eta^3 - 0.0241\eta^2 + 0.0053\eta \tag{10a}$$
$$B = -0.0001 \tag{10b}$$
$$D = 1.1261\eta - 0.3031 \tag{10c}$$
$$E = -1.0178\eta^3 + 0.3059\eta^2 - 0.0218\eta + 0.0004 \tag{10d}$$
$$F = -2.5167\eta^3 - 0.2653\eta^2 + 1.0076\eta + 0.5003 \tag{10e}$$

2.4.1 An Example

Suppose that we wish to calculate β for an observed sand wave field with typical parameters $\lambda = 10.0$ m, $h = 1.25$ m. The sand waves are known to be slightly asymmetric due to a unidirectional current coupled with wave action. An arbitrary first guess of phase factor, $\phi = 80°$ (or $\phi' = 2.22$ m), is made. In this case, $\eta = 0.125$ and $u = -0.03$. From Eqs. (9) get $A = 0.0004$, $B = 0.0000$, $C = 0.0166$, $D = 0.0000$, and $E = 0.3812$. Therefore, Eq. (8) becomes

$$\begin{aligned} \beta &= 0.0004u^4 + 0.0166u^2 + 0.3812 \\ &= 0.3812. \end{aligned}$$

[4] Originally written by J. N. Little, 1985, revised by others, final revision 1997.

Further suppose that the observed sand wave that we wish to model had a measured β of 0.325. From Table 3 it can be seen that the most asymmetric sand wave possible for $\eta = 0.125$ is between 0.40 and 0.36 (the values for $\eta = 0.10$ and 0.15 at $\phi = 90°$). This shows that unscaled Eq. (3) cannot produce the needed β for the given η. However, a β of 0.326 is possible with $\eta = 0.21$ and $\phi = 72°$. Therefore, by taking $\eta' = 0.20$ and $\overline{\phi} = 73°$ (or $\overline{\phi}' = 2.03$ m), Eqs. (9) give $A = 0.0026$, $C = 0.0108$, $E = 0.3247$, and $B = D = 0.0000$, for a symmetry parameter of

$$\beta = 0.3252 \cong 0.325.$$

Once the values of η' and ϕ leading to the correct symmetry for the sand wave have been selected, the equation can be scaled as previously described. The scale factor is $C = \frac{\eta}{\eta'} = 0.625$. Therefore, the sand wave profiles will be generated from

$$z = 0.625 \times \left\{ \frac{h}{2} \left[1 + \cos \left\{ \frac{2\pi}{\lambda} \left(x + \frac{h}{2} \sin \frac{2\pi}{\lambda} x \right) + \phi \right\} \right] \right\},$$

where $h = 2.00$ m (the height needed to get $\eta' = 0.20$ with the measured λ), $\lambda = 10.0$ m, and $\phi = \overline{\phi} = 73° = \frac{73\pi}{180}$.

It is also possible to go directly from Table 3 to the equation by interpolating between the values given in the table to the desired values, if necessary. Interpolation is not quite as precise as the calculation, but is adequate for most purposes.

There is one catch to this calculation, regardless of how it is accomplished. For $\eta = 0.21$, $\phi = 72°$ is not the only ϕ giving the desired β. $\phi = 108°$ does also. However, the profiles produced from the two ϕ's are not the same (see Fig. 6). Therefore, descriptions of the sand waves to be modeled are almost as important as the correct parameters.

3. SAND WAVE EQUATION APPLICATIONS TO SONAR MODELING

3.1 1D BaGM Modules

For typical acoustic ray trace applications where the region of interest may span several kilometers, the sea floor is represented by a series of single radials using the one (free) dimension form of the sand wave equation, Eq. (3). The two-dimensional features of the sea floor are represented by sets of these radials. At present, information about the sand wave orientation with respect to the observation direction is included by changing the sand wavelength used in Eq. (3) to an effective sand wavelength, related to the original sand wavelength by $\lambda_{\text{effective}} = \lambda / \cos\theta$, where $\theta \equiv$ the angle between the perpendicular to the crest line and the actual observation direction. This is because the reverberation model with which BaGM (1D) has been used so far treats all encountered sand waves as if their crests are perpendicular to the observation direction.

Multiple overlying bedforms can be represented by adding the heights of the various features, using the same radial steps. In this way, sea floors such as a slope with large dunes and overlying mega ripples can be modeled The minimum number of BaGM generated data points needed to represent a single bathymetric feature is five, but typically more are required to satisfactorily show the profile details, particularly if the profile is asymmetric. This requirement, the maximum number of allowed data points, and the size of the region to be represented place a lower limit on the size of the bathymetric features that can be represented. BaGM data files consist of range vs height values along each radial.

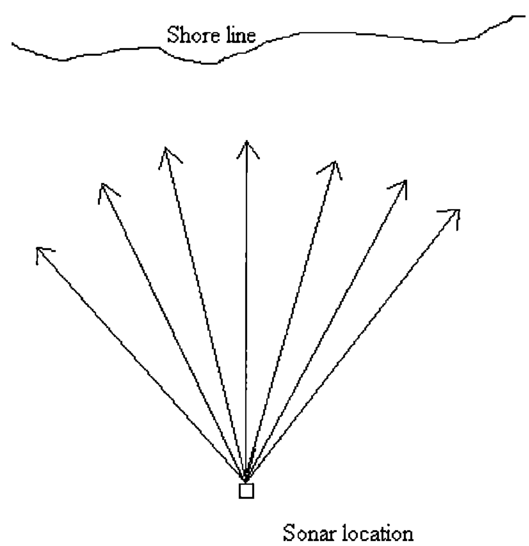


Fig. 11– Graphical representation of a typical sonar and shore configuration. The x' -direction for each radial is defined as the observation direction (the direction of the arrow corresponding to that radial). Typically, the x-axis corresponds to the center radial.

3.1.1 Typical Sonar Radials

The first sonar type considered in connection with BaGM stays in a single location and scans the region with successive sonar pulses along a radial fan originating at the sonar. With this type of sonar, the path of each pulse is separated by the pulse beam width, so that the entire region is insonified. Figure 11 shows a typical sonar/shore line system with arrows representing the radials along which the bathymetry data files are calculated. Each radial defines the center of a sonar pulse. Consequently, the original set of bathymetry programs, ripple#.f, has become one module of BaGM, referred to as "Standard BaGM." Appendix B describes the current version of this module program, its flow chart, and auxiliary programs used in conjunction with the module, and presents examples of the input data file and output summary file and the output data file structure and naming convention.

Usually, the number of single sea floor radials generated corresponds to a typical number of observations for the type of sonar. The origin of the 1D, x'-coordinate system of each radial starts at the sonar location and points in the observation direction, with the orientation changing with the radial. The center radial defines the x-direction, which is taken to be perpendicular to the sand wave crests. In Fig. 11, this radial is directed towards the shoreline, though this is not a requirement of the model. In a typical application, the angular spacing between successive radials is usually set to approximately the angular width of the main beam of the sonar in question, although some other interval may be selected. For very large regions, at great ranges, small angular spacings can produce large physical spacings. This typically means that in the region directly illuminated by the sonar, the bathymetry radials, which trace the center of the sonar beam, are separated by several sand wavelengths. Consequently in this module, all bathymetry radials have the same random starting point and regional sea floor parameters, but are otherwise generated independent of one another. In other words, the sand wave type, λ, h, ϕ, and δ are selected for each of the multiple bedforms in the sand wave field and are used in all sonar paths making up the region. However, the model does not "remember" any details of previously generated paths as it generates successive paths. For long-crested sand waves, this distinction is not important, but for other sea floor patterns, particularly short-, intermediate-, and wavy long-crested sand waves, it is important, since they have additional random

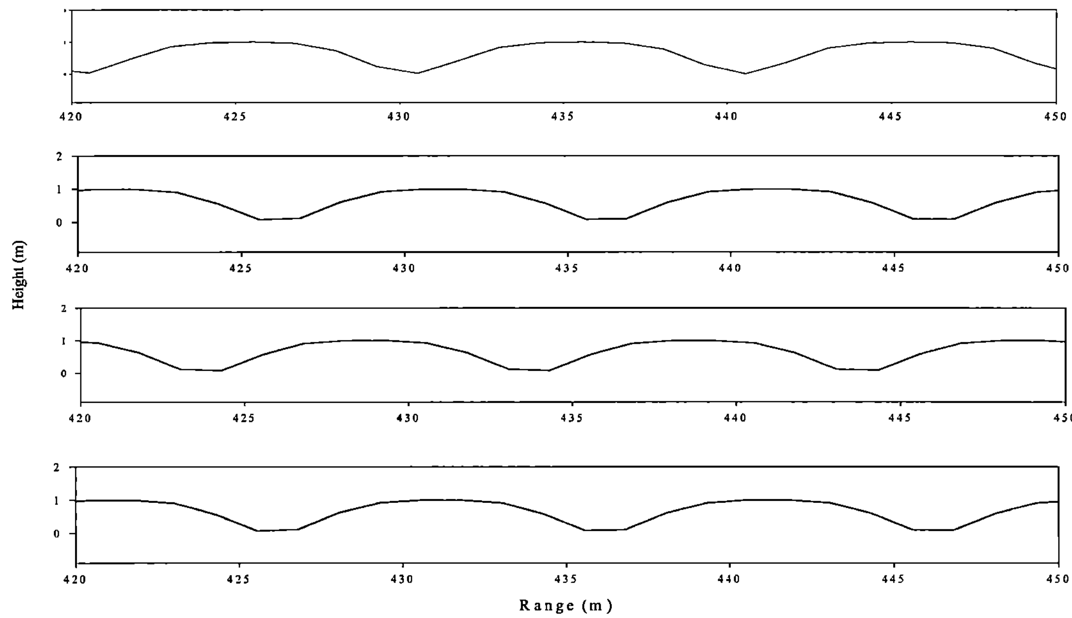


Fig. 12– BaGM-generated sand wave profiles. Pattern is similar to that of symmetric tide-generated sand waves.

parameters governing crest heights or position. Appendix A describes the various parameters and input necessary for representation of each of the sand wave types.

Figures 12 and 13 are sand wave profiles and the resultant bathymetric representation of a tide-generated symmetric sand wave field. The displayed sand waves have λ of 10.0 m and a maximum height of 1.0 m. The step size for each radial is 1.2516 m, giving approximately eight points per sand wave. The sand waves in Fig. 13 look curved as a consequence of plotting polar radials in a rectangular coordinate frame. Plotted in polar coordinates (refer to Fig. 11 for a sample ray pattern), the crests would be straight.

3.1.2 Sidescan Sonar Beams

Sidescan sonars send out beams along parallel paths (Fig. 14). The advantage of this is that the spacing between the beams does not increase with distance from the sonar. However, the close connection between bathymetry paths requires a modification in the way in which variable crest sea floors are represented in the bathymetry model.

As in the previous module, the sand wave type, characteristics (λ, h, ϕ), and δ are selected for each of the bedforms in the sand wave field and are used in all sonar paths making up the region. However, using random variables to determine the maximum crest height for short- or intermediate-crested sand waves in successive paths is not sufficient because individual crests might span two or more bathymetry paths, even at great distances from the sonar. Consequently, both the position on the crest and the crest length are randomly selected for each sand wave encountered along the first bathymetry path, with the positions on the crests of successive paths determined by the selected crest length and spacing between those paths. The sand wave parameters determining the positions along the crest are saved in an array. The maximum size of the array places a maximum value on the number of sand waves possible along a single path; however, the array is large enough to accommodate most possible sea floors, and its dimensions can be easily increased if needed to accommodate additional features. Appendix C has descriptions of both versions of this module program, the flow chart of the more recent version, a description of the water-depth

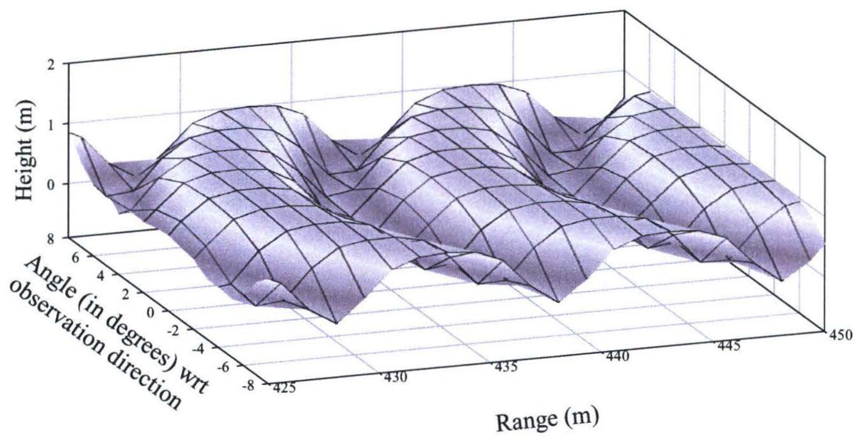


Fig. 13– Tide-generated symmetric sand waves. The crests appear curved because the sand wavelength is adjusted to account for the increase in the distance between crests when the observation path is not perpendicular to the crest line. In polar coordinates the crest lines would be straight.

program used in conjunction with the module, descriptions and examples of the input data file and output summary file, and the output data file naming convention.

Figures 15 and 16 show sidescan sonar bathymetry of two regions of short-crested sand waves. Both regions contain asymmetric sand waves of the current/wave-current generated pattern, both have the current flowing in the same direction as the observation direction. Figure 15 which shows typical profiles along paths in the two regions, illustrates the random crest height selection effect. Short-crested sand waves are defined to be those that have crest lengths of one to three times the sand wavelength. In these paths, it can be seen that approximately one third of the crests are reduced in height from the selected sand wave height. The shorter of the sand wavelengths is approximately half that of the larger; both sets have $\eta = 0.10$. Figure 16 is a gray-scale plot of these two regions. The height above the lowest point on the sand waves is represented by the gradations in shade, where the lighter the shade, the higher the point. In this figure, the division between the two bedforms is abrupt. In the actual area represented by this modeled sea floor, the two bedforms were separated by a wedge-shaped muddy region. Since the client already had a mechanism for adding odd shaped features, the muddy region was added to the sea floor later as a modification. BaGM currently can represent the sea floor complete with the muddy region, but the boundaries of the region are stepped rather than smoothly angled (sloping region definitions are to be added to the model in the future).

3.2 2D BaGM Module

One question in high frequency acoustic reverberation modeling has been related to the effects of small ripples overlying larger bedforms. Experimenters report that the small ripples are the primary source of acoustic clutter in their observations. However, computer modeling to optimize sonar performance over large areas ($\sim$ 1 km^2 or larger) of necessity operates on grid sizes much larger than these small-scale features. Also, features smaller than the sonar pulse lengths (in meters) are statistically averaged in the return signal. Consequently, the modeler often assumes that ripples smaller than the pulse length are insignificant. Even when the small-scale features are not deemed insignificant, they can be difficult to include in acoustic models. The version of BaGM based on Eq. (4) (wedge2.f, wedge3.f, and wedge4.f or

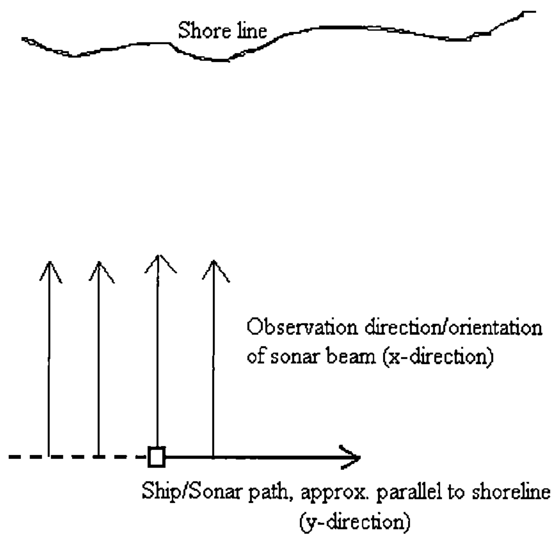


Fig. 14– Sidescan sonar shoreline/observation direction orientation. The observation direction is shown towards the shore, with the motion of the ship/sonar parallel to the shore, though this is not a requirement. The observation direction is defined as the x-direction while the direction that the ship travels is the y-direction.

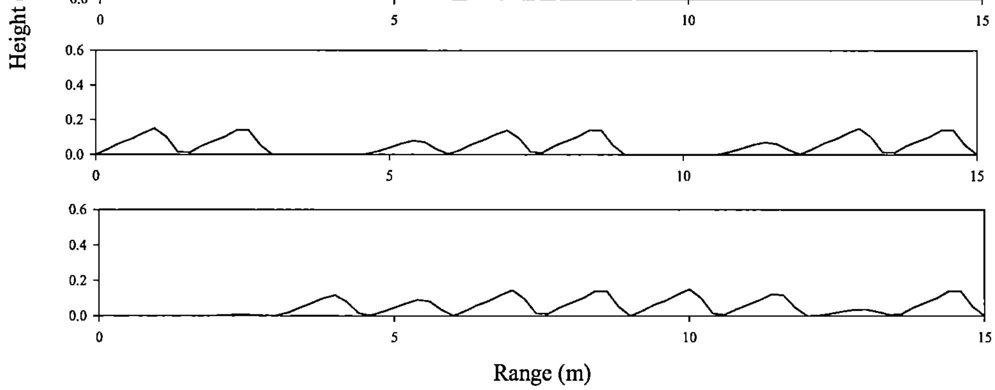


Fig. 15– BaGM-sidescan generated asymmetric wave-current sand wave profiles. The variation in sand wave height along a path is due to the pattern choice of short-crested sand waves. The variation reflects the fact that a single path will intersect different sand waves at different points along the crest.

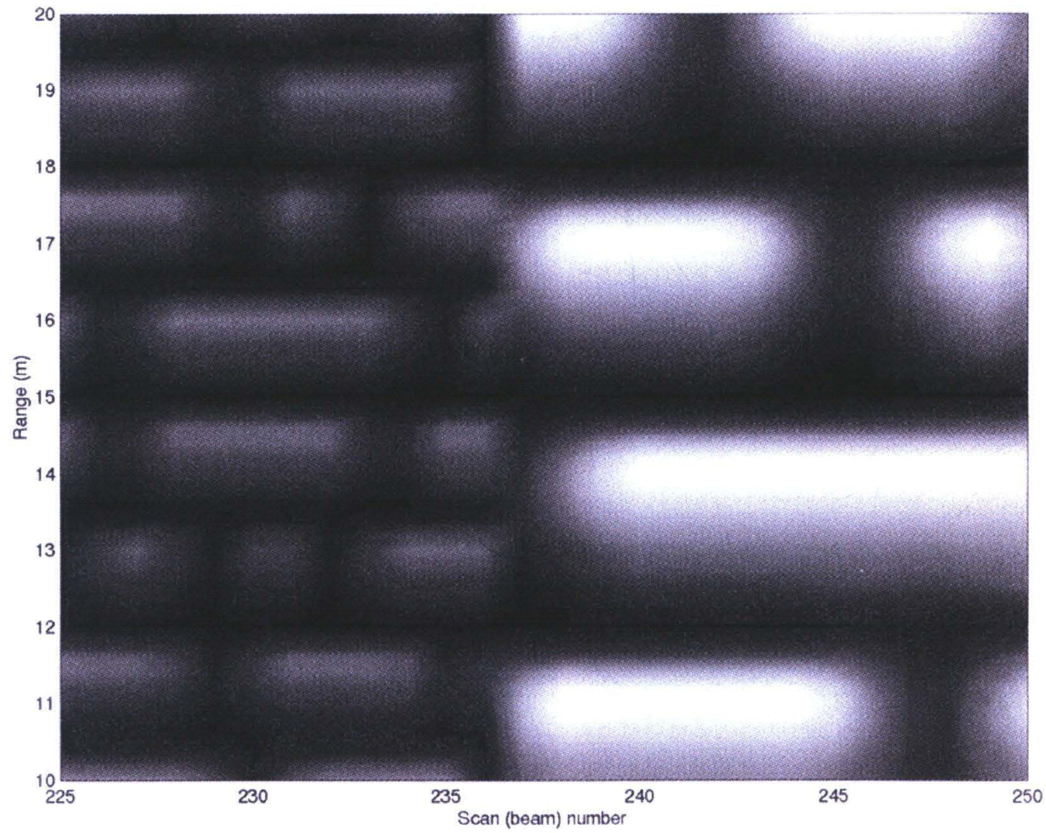


Fig. 16– Plot of an area consisting of two regions of asymmetric, short-crested sand waves. The y-step, each step corresponding to a scan or beam number, is 0.2 m.

BaGM-3D[5]) was developed to fulfill the dual purpose of evaluating the significance of small scale ripples on the acoustic backscatter and providing a method to characterize their effects statistically so that these effects can be included in acoustic reverberation models. The wedge3.f and wedge4.f program flow chart and a description of the input data files are given in Appendix D.

BaGM-3D can be used to represent large regions, although its primary utility comes from the detail that can be introduced into the bathymetry through the fine grid size. Figure 17(a) represents a small slice of a sand wave, Fig. 17(b) shows the same sand wave with overlying micro-ripples. The basic sand wave featured is a slightly asymmetric, wave-current-generated sand wave with $\lambda = 5.0$ m and maximum height of 0.5 m. The overlying micro-ripples consist of both short-crested and random sand wave patterns. The grid point spacing is 0.005 m in both the x- and y- directions. The basic sand wave is oriented at $\theta = 20°$ with respect to the observation direction. Figure 18 shows a set of BaGM-3D profiles extracted from the bathymetry displayed in Fig. 17(b). Due to system memory limitations, this type of detail cannot be represented in the large regions for which the 1D versions of BaGM are optimized.

The BaGM-3D sea floors shown in Fig. 17 were used with Keiffer's Wedge Assemblage Scattering Program (WASP) [14] to demonstrate conclusively that the small ripples have a significant impact on the

[5] Typically small scale bathymetry models that represent complete sand ripples are referred to as 3D models. Acoustic models applied to the same region are usually referred to as 2D models. The dimensionality of BaGM in this report is based on the acoustic model convention. However, this module was named and has been referenced using the bathymetry convention, hence the name BaGM-3D.

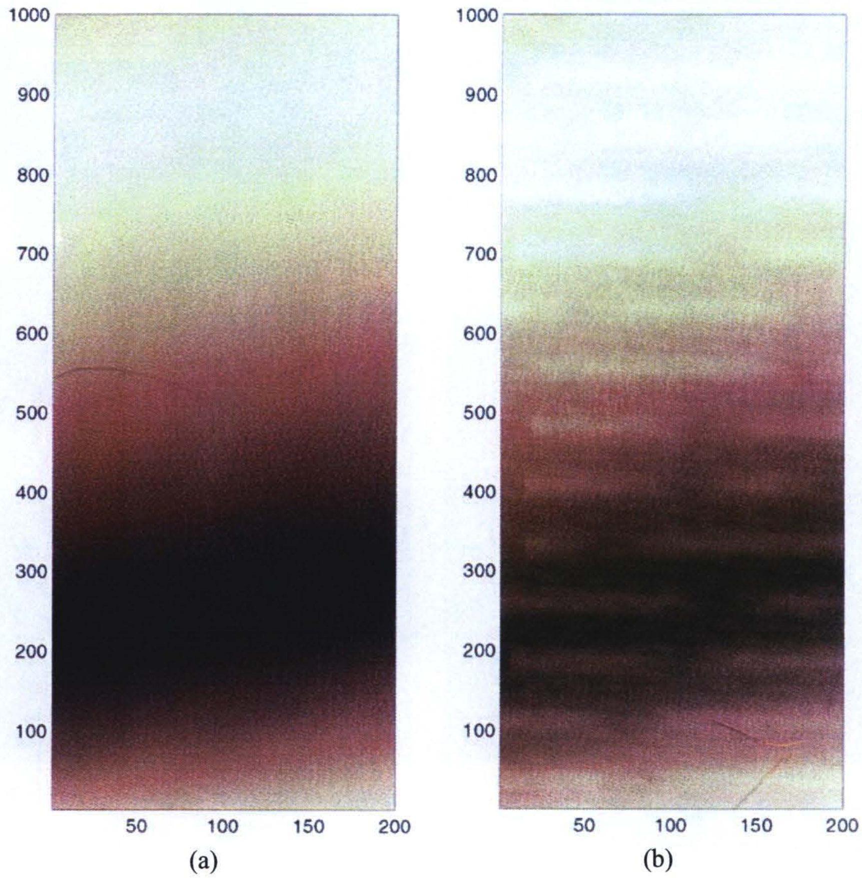


Fig. 17– Pseudo-color plots of BaGM-3D produced bathymetry showing (a) a basic sand wave, and (b) the same sand wave with overlying short-crested and random micro-ripples. The values on the axes are the number of grid points, where the grip point spacing is 0.005 m in both the x- and the y- directions.

acoustic scattering strength over a wide range of frequencies. The two sea floors were evaluated at two orientation angles and one grazing angle, then backscattering strengths were compared. There were significant differences between the results for the two sea floors [15]. Finding an efficient way to include these features became desirable. It was concluded that the most efficient way to include small scale bathymetric features and out-of-plane scatter is statistically. Consequently, BaGM-3D and WASP have been used together in developing statistical characterizations of the scattering strengths from different patterns and orientations of small ripples .

This module of BaGM is essentially a small scale feature/micro-ripple model. As such, it is not computationally suitable for sonar perfomance predictions. The wedge.f program was developed to test and study the effects of this micro-roughness[6] on acoustic backscattering strengths. The module is to be used in conjunction with other BaGM modules; BaGM-3D will determine statistical variations in the sea floor material scattering strengths based on the type or degree of micro-roughness in the sea floor.

[6] For the purposes of this report, micro-roughness refers to any feature that is smaller than the sonar pulse length or the minimum step size of the BaGM module used with the acoustic model, whichever is larger.

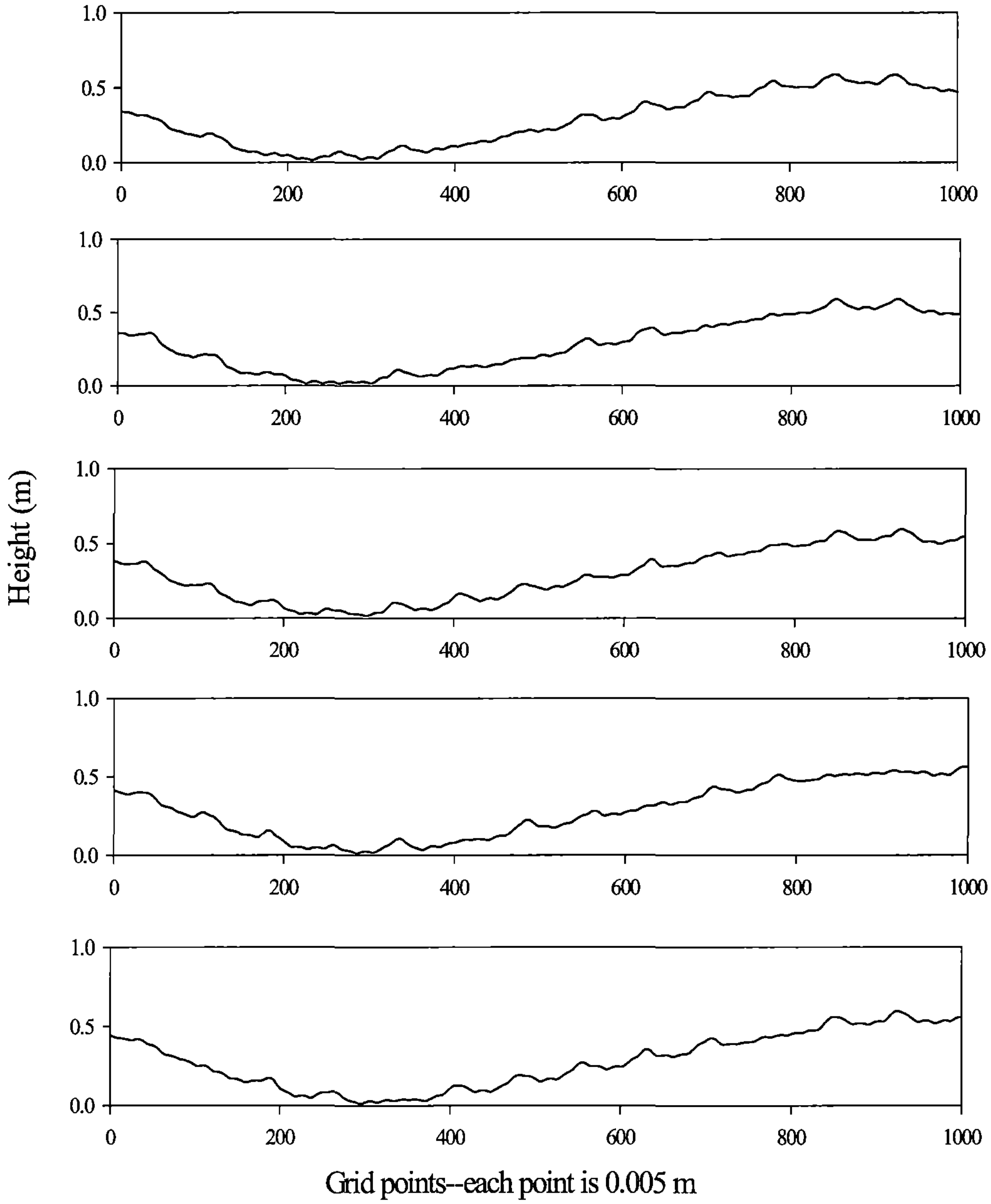


Fig. 18– Bathymetry profiles extracted from Fig. 17(b)

3.3 Expanding the Horizons of 1D and 2D Sea Floor Representations

Sometimes, it is necessary to model a large region using a 2D/3D representation. The flexibility of BaGM was conclusively demonstrated when the BaGM-3D module was successfully used to represent an area 22 km on the side, containing regions of differing materials, sand wave types, and miscellaneous objects (e.g. rocks, slopes, and scour regions). Unlike the very small patches containing small scale feature/micro-ripple representation, to which the model was previously applied, it could not be assumed that the same type of features and sea floor material spanned the entire region of interest. In fact, it was known that this was not the case. Therefore, an additional subroutine was added to the model. In this case, a position-dependent scale factor for Eq. (4) was defined. Different bathymetric features, even overlying features, are modeled separately then combined by adding the separate files to create a single sea floor file. Therefore, for each bathymetric feature, the scale factor is reduced or set to zero where the feature is declining or not present. The full region complete with patch specific bathymetric features was then produced by adding the bathymetric specific data files.

Individual parallel radials in the BaGM-SS format can be extracted from the bathymetry file produced in BaGM-3D. The radials may cover the entire region represented in the BaGM-3D file or a selected part. These individual radials can be operated upon as if they were produced in the BaGM-SS module.

Sometimes, it is very nice to compare the results from both types of "sonars." For very simple cases, such as long-crested sand waves over a large region, this can be done by putting the same parameters into both 1D BaGM modules. The results of this will be very similar to using the same sea floor, with the major difference in the starting point on the first sand wave. However, for sea floors with changing parameters across the region or different sea floor types in the region, using the same parameters in both modules is not an option, as the BaGM-1D module is not flexible enough to accomodate these features. Furthermore, at times it would be nice to model a complex region for the standard sonar type. This cannot be done with the BaGM-1D module. Therefore, a composite module, based on the BaGM-SS has been developed.

This module, BaGM-cmb (see Appendix E), will, in time, replace both the BaGM-1D and BaGM-SS modules. As in BaGM-SS, the sea floor is represented by parallel radials (y dimension), in the form of range (x), height (z) pairs. The area (y) dimension is saved as separate files. The grid density for sea floors represented in this module should be greater than necessary for representing sidescan sonar beams since it is a "generic" sea floor, rather than one developed specifically for use in modeling sidescan sonar reverberation. This resultant sea floor can then be used with several different "types" of sonars having different configurations and beam spacing. This module can either generate a new sea floor with representations in both the BaGM-SS or BaGM-1D formats or it can use an existing BaGM-SS type sea floor–such as one extracted from a BaGM-3D bathymetry file–and can extract the user's choice of only the BaGM-1D radials, both BaGM-SS and BaGM-1D, or only BaGM-SS radials with a modified spacing.

Bathymetry radials for use in modeling sonar performance can be extracted from the sea floor. This is done by selecting a starting point on the sea floor for the sonar, near the center for standard sonar, near the origin for sidescan sonar, beam spacing, and range step size. Then, for each point along the radial, the sea floor height is found by interpolating between the heights of the four nearest sea floor grid points. This has a collateral advantage that it allows a random factor in addition to δ (see Section 2.1.1) to be introduced into the modeling so that averaging multiple run results will better represent the true situation.

At present, the various BaGM modules are independent programs. However, as the model matures, the interdependence of the modules grows. Eventually, a master "program" in which the various components are subprograms (or modules in the FORTRAN 90/95 sense) will be desireable and quite possibly essential. There are several advantages to grouping all parts of the model under a single "umbrella"; one is the cross-module availability of features. For example, cuspate sand waves can be directly represented in BaGM-3D

only. However, by extracting BaGM-SS type radials from the BaGM-3D data files, then applying the module described above, cuspate waves can be represented in all three formats.

4. BaGM REQUIREMENTS AND PLANS

Theoretically, BaGM can produce sandy sea floor bathymetries to any resolution desired, on any scale. In practice, the model is limited by CPU time and computer system memory, with further constraints introduced by input bathymetry data file requirements of the models or systems with which the BaGM results are used. Although Figs. 11 and 14 show the observation direction towards the shoreline, that is not required. The origin of the BaGM coordinate system of sea floors for use with the typical sonar types is at the sonar location. This is not a model requirement, either, and the BaGM-3D sea floors are produced independent of any observation point.

BaGM is used by following the steps listed below:

- determine which module best suits the problem to be explored
- write or modify the input data file (the format, needed information, and parameter codes are described in Appendixes B, C, and D, for BaGM-1D, BaGM-SS, and BaGM-3D, respectively).
- run the program corresponding to the selected module

The BaGM modules described in this report have been optimized for specific purposes. However, adding BaGM modules, using either the 1D or the 2D sand wave equations, that are optimized for other applications is not difficult. The model is applicable any time detailed bathymetric information is of use. The size of the region and the resolution of the sea floor are application dependent. There are no constraints on the depth of the water in the sample region; 1D BaGM sea floors are presently being used to predict bathymetry dependent shallow water (10 to 100 m) acoustic reverberation [16–18]. BaGM-3D sea floors are being used to model the acoustic scatter from small scale sand ripples [15] and predict changes in scattering characteristics of the sea floor material due to the roughness of the features.

4.1 Computer System Parameters

The various BaGM modules and auxiliary programs are written in FORTAN 77. However, as BaGM grows and matures, conversion to FORTRAN 90/95 will take place. There are several areas where FORTRAN 90/95 will greatly simplify the computing process. The BaGM modules are installed and in use on a SUN SPARC20 system running UNIX with a Solaris 2.6 OpenWin operating system. The system random number generator is used in the program to get the seed value for a system-independent random number generator that calculates the random numbers used in the sand wave equations. Random numbers are used in all BaGM modules to calculate δ, position along the crest line of the variable crest sand waves, and random orientation angles for the random sand wave pattern.

The different modules of BaGM require different information to represent the sea floor. Therefore, they read the data in from type-specific data files described in the appendixes. However, all input data files use the same sand wave type codes listed in Appendix A.

4.2 Planned Model Enhancements

Both 1D BaGM modules allow multiple regions, characterized by different sand wave types sizes or patterns, in the area represented. However, the shapes of these regions are very limited. In Standard BaGM, divisions between the regions are possible only in the x-direction. Any changes in the regions with radial or angle with respect to the crest line are made by using multiple BaGM runs, with the data files renamed to make a complete set. BaGM–Sidescan allows divisions in y-direction, but a sloping division

between regions is represented by a series of steps. Efforts are being made to improve the y-coordinate (or radial) dependence of the divisions between regions in BaGM bathymetry, allowing for representation of non-rectangular regions. This will include defining a transition region that more smoothly blends the intersections of regions having different sand wave patterns.

Although BaGM sea floors are static, time-dependent bathymetric features, such as tide-cyclic patterns in the sand wave crest orientations, can be represented by producing successive sea floors reflecting the time-dependent changes in the observed parameters. Mobile sand waves, important in mine burial predictions, can be modeled in a similar manner, although the effect of stationary features such as mines, large rocks, and coral outcroppings on the sand wave patterns must be accounted for to ensure accurate predictions. It has been demonstrated [19] that bathymetric features influence the flow of currents and alter patterns of wave-based sand entrainment. BaGM sea floors are potential candidates for studying these phenomena computationally.

It is believed, though not yet verified, that the sand wave equation used in BaGM can be extended to represent other sea floor materials, particularly mud and silt. At present, the sea floor materials used in the model are restricted to sands. However, this is because bathymetry pattern limits for other materials are not yet known. For example, materials such as silt and sandy silt form ripples, but may not form larger features; gravels tend to form larger structures, but even if formed, small ripples would be hard to identify. As the parameters required to make the equation valid for other materials are determined through study of observed features of these materials, BaGM will be extended to include them.

The acoustic model currently used with the 1D versions of BaGM assumes all sand wave crests are perpendicular to the observation direction. This deficiency can be addressed by including grazing angle effects on the acoustic backscatter in the parameters representing the sea floor material scattering strength. The acoustic model uses scattering strength data files that allow the user to specify the numeric scattering strength of the sea floor material. Up to 40 changes in the sea floor material scattering strength are allowed in these files, so that changes in sea floor material with location can be considered in the acoustic model. BaGM is currently undergoing modifications to include options for writing sea floor scattering strength data files as well as sea floor height vs position data files. The scattering strength data files will include the effects of sea floor material, grazing angle, and micro-roughness.

The idea of combining models based on the root mean square (RMS) roughness of the surface with BaGM is being explored. The plan is to combine BaGM profiles with RMS model type crest positions. This is because RMS models generally produce the variable crest positions that are more typical of observations, but their sand wave profiles are uniformly sinusoidal, an unlikely occurrence in nature. Therefore, a combination model has the greatest probability of representing the actual sea floor. A subroutine capable of setting the peak of a BaGM-produced sand wave profile at the desired position has been written but is not currently in use.

5. SUMMARY

5.1 Conclusion

The Bathymetry Generation Model (BaGM) is applicable anytime detailed representation of the sea floor is important. It allows representations of a very wide variety of bathymetry types and patterns, including asymmetric patterns, based on observable parameters. This is the most flexible and easy to use bathymetry model known to the author. The model does not predict the bathymetry in a given region, but if the bathymetry is known, BaGM can be used to represent that bathymetry in acoustic and sonar prediction models. Since BaGM is not limited to single types of sea floors, it can be used to generate representations of both simple and complex sea floors. BaGM is designed for near-shore and continental shelf applications. If desired, it could be extended to include ocean basin, sea mount, and oceanic ridge features; however, there are several models that work well in these regions, so extending BaGM to this regime is not anticipated.

At present, BaGM is limited to sand or other hard surface regions. There are two reasons for this. First, there is not yet a mechanism for including penetration effects of the acoustic waves, and second, the feature profile limits for materials other than sand have not yet been identified for inclusion. No doubt the sea floor profile equations used in BaGM can be configured to include the bathymetric patterns found in mud and silt, which could affect the absorption of acoustic energy. At present, gravels or rocks included in BaGM are represented by flat beds or very low height to length ratio waves, or added "solitary objects" that are appended to the sea floor data files.

As with any model, there are tradeoffs between what can be produced and what the real world is like. BaGM includes the most sand sea floor patterns of any model known and is easiest to use. However, the features that it generates tend to be much more regular and deterministic than are found in littoral seas. RMS models have profile patterns that tend to be more like those observed. However, such models cannot produce the wide range of bathymetric profile patterns found in nature, nor some of the more regular patterns. A combination model including features from BaGM and RMS models has the greatest probability of accurately reproducing the observed sea floor features. Such an improvement is planned for BaGM in the future.

Muds and silts are common on the continental shelves and near-shore environments. Expanding BaGM to include the observed patterns and profile shapes for these materials can be accomplished by studying observations of these regions and determining the ripple or wave parameters that will produce these features. This process is more time consuming than difficult. However, these materials allow penetration by a large range of acoustic frequencies. Consequently, buried materials that may or may not be known, as well as the sub-sea floor, play a part in sonar performance. Most likely BaGM can be configured to generate sub-sea floor features as well as the sea floor features. However, including the acoustic properties of a mud layer, sub-sea floor, buried materials, or sub-surface gas bubbles is not within the realm of BaGM as it currently is formulated. A new program or extensive expansion of the present model, designed to consider much more fully sea floor composition, substructure, and inclusions, is required to evaluate the full acoustic effect.

BaGM is not a predictive program. It includes no formation mechanisms and is limited to representing the observed features. Consequently, for BaGM predictions to be useful in a specific region, observations or predictions of the features in that region must first be made. It is hoped that a model capable of predicting the overall types and relative scales of bathymetric features based on environmental factors will be located or developed. Such a model can be used in connection with BaGM to produce reliable/usable sample sea floors of regions where direct observations are difficult or impossible. One potential such model [20] has shown a great deal of promise in areas near Great Britain, however, it requires on-site current and wave measurements. Testing to verify it can do as well with predicted currents and waves and is applicable in other regions is needed.

The flexibility of BaGM is greatly enhanced by several companion programs that either manipulate BaGM data files or, as in the case of 'mkapluw.f', write data files to accompany BaGM data files when used with acoustic models. These companion programs are described at the end of the appendix describing the capabilities of the BaGM module with which they are used.

5.2 Non-Navy Applications

Although the model was developed to address a specific issue of concern to the Navy, namely the mine countermeasures problem, its use is not limited to naval applications.

5.2.1 Overseas Uses

5.2.1.1 Europe: Norway, England, Italy; Japan

BaGM can be of use anywhere detailed studies of the ocean floor are carried out and where sonar are used. BaGM does not by itself do anything on the acoustic end–it is for use *with* acoustic models. Current research is being carried out using one module of BaGM that will lead to BaGM writing the sea floor scattering files as well as the bathymetry files. When this is done, BaGM will include sea floor material and sea floor roughness on scales in which sea floor roughness has been neglected in the past. Interest in the model has been expressed by a researcher from NATO SACLANT Underseas Research Center who visited NRL-SSC. SACLANTCEN currently uses an RMS roughness model for sea floor generation. It is very successful at reproducing observed sand wave and sand ripple crest line patterns for long-, intermediate-, and short-crested sand waves, but all profiles produced in this type of model are sinusoidal.

5.2.1.2 Australia

The bathymetry in the waterways off the east coast of Australia is dominated by large asymmetric, mobile sand waves caused by strong currents through the straits. These sand waves are of concern to the Australians because they can bury objects lying on the sea floor. The Australian Navy [13] is very concerned about the possibility of mine burial by these mobile sand waves. Consequently they have instituted studies to look at the mobility of and mine burial capabilities of the sand waves. In the technical report that I reviewed of one such study, a simple sawtooth pattern was used to represent the sand waves. This same shape was then stepped across the region of interest to simulate the movement of a sand wave. This technique allows the researcher to consider the effects on sonar and burial of the different positions of the wave, but fails to consider the method by which the sand waves move and profile shape changes inherent in that motion. BaGM can represent a wide variety of sand wave profiles, including sawtooth patterns. Therefore, using BaGM for mobile sand wave and burial problem research would allow the researcher to consider the effects of the changing sand wave profile as well as the motion of the sand wave across the region. Furthermore, there are three-dimensional effects stemming from water flow around sea floor surface objects that cannot be considered by the general one-dimensional sawtooth pattern, but can be included in BaGM-3D and to a limited extent in BaGM-Sidescan for a more realistic representation of a sea bed consisting of large, mobile sand waves under moderate-to-strong current conditions.

5.2.2 Commercial Applications

5.2.2.1 Universities or Other Ocean Research Facilities

BaGM is of potential use to oceanography and marine geosciences departments at universities and other ocean/marine research facilities for the same reasons that it may be of use in overseas applications. It can represent more sand wave patterns and profiles than any other model we have found. One project of interest is how rippled sea floors affect the flow and transport of sediment. BaGM can produce realistic sand wave

profiles/sea floor patterns that can be used to represent such sea floors in models or experiments studying these processes.

5.2.2.2 Fisheries Use

When sonar is used to locate commercial fish, there is a part of the water column, called the "shadow zone" or "dead zone," near the sea floor where reverberation from the sea floor masks any possible signal from fish. The depth of this region can be reduced by using deep towed transducers [21], but not entirely removed. This makes acoustic detection of bottom dwelling fish or shellfish very difficult to impossible. Even returns from the types of shellfish that have shells that produce very high reverberation levels may be mimiced or masked by small ripples on sandy sea floors. Although there is no guarantee that BaGM results can be used to further reduce the depth of the dead zone, it may provide a postprocessing refinement that can be used for this purpose.

5.2.2.3 Location of Aircraft Parts After a Plane Crash

Recently there have been several highly publicized plane crashes in which the aircraft went into coastal oceans. In all of these cases, locating the scattered parts of the aircraft in the search and rescue/search and recovery process has been challenging. It is believed that BaGM, along with a sufficiently sophisticated acoustic model, might be useful in the search phase of such missions. If the basic sea floor patterns in the region that is to be searched are known, BaGM can be used to identify which regions are most likely to have a high probability of false targets, allowing searchers to concentrate their efforts in areas that are less likely to have false targets yet show higher than expected returns for the sea floor pattern.

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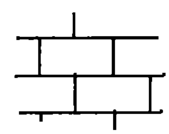
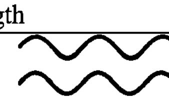
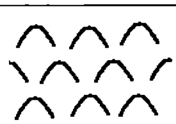
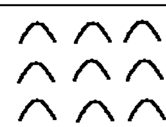
Appendix A

DEFINITIONS OF SAND WAVE TYPES

SAND WAVE TYPE CODE

Table A–1 lists the sand wave crest patterns that are available in BaGM. Not all patterns are presently available in every module, but will be present in the final versions, if possible. Any pattern available in BaGM-3D can be translated into the 1-D forms as described in Section 3.3. The first column in the table, **sand wave type code**, is used in the input data files to specify the type of sand wave to be modeled. The second column is the sand wave crest pattern, and the third column is the definition of the sand wave crest pattern, either from the literature, as used in BaGM or both.

Table A–1– Sand Wave Crest Patterns

Sand Wave Type Code	Sand Wave Crest Pattern	Definintion
1	Long-crested	crest length $\geq 8\lambda$. In this model, they span the region or observation range (can be changed)
2	Intermediate-crested	$3\lambda \leq$ crest length $< 8\lambda$. Model provides various choices for crest length range.
3	Short-crested	crest length $\leq 3\lambda$
4	Brick pattern*	long-crested sandwave bisected by $\perp$ short-crested at $\frac{1}{2}\lambda$ intervals between successive long-crested waves 
5	Random	currently sets of added long-crested; also need to consider random height selection with some correlation length
6	Wavy-long-crested	as long-crested with periodic oscillation in crest line 
7	Linguoid**	 horseshoe shaped pattern
8	Cuspate*	 horseshoe shaped pattern
9	Modified random	same as random, except the sand wave combined height is handled differently
* Not presently available in all BaGM modules		
** Not presently available in any BaGM module		

SAND WAVE PARAMETER LISTS

The BaGM modules each have an input file that contains the parameters used by the various programs to produce the desired sand wave patterns. For the most part, the parameter sets for a given choice of sand wave crest pattern are the same for most module programs. So far, the exceptions are ripple5.f and wedge3.f. The structure of the input file for these programs differ from the others and each other because they have many special features not found in the other programs/modules. The parameter sets for the sand wave patterns are listed below. These values appear in the input data file immediately following the sand wave type code, *in the order in which they are listed.* A line is included in the data file only when it applies to the selected type of sand wave. For variable crest height sea floor patterns, the length of the crest is randomly selected from the defined length for the sand wave type (in the case of intermediate sand waves, this can be user selected), then the position along the crest is randomly selected. If the selected position is within $\frac{\lambda}{4}$ of an end of the sand wave, then the maximum crest height is linearly scaled with the distance from the end of the sand wave.

Long- and Short-crested and Brick Pattern

- Orientation angle, θ: determines the angle of the sand wave with respect to the observation direction. Possible range from 0.00 to 180 degrees. Not presently used in standard BaGM program ripple5.f
- Sand wavelength, λ: user selected, generally should be at least 5 times the step size used.
- Phase shift, ϕ: determines the sand wave symmetry, also influences the starting point on the sand wave profile. Entered in degrees, may range from 0 to 360.
- Trough length: set equal to zero for trochoidal sand waves, non-zero for solitary sand waves. At present, representations of solitary sand waves are not possible.
- Sand wave height, h: the amplitude of the sand wave. Selected values are not limited, but the theoretically and experimentally valid range is from 0.0001 to 0.21λ. Values up to 0.25λ may be used if the sand wave is scaled.
- Scale factor, C: used in the sand wave equation to access more asymmetric profiles for low η sand waves.
- Sand grain size: in mm, not currently used with the model. Applies to sea floor scattering strengths in sonar models.
- Number of wavelengths for a change of 2π: applies to long-crested patterns only, varies the phase shift and, therefore, symmetry parameter of the sand wave across the region in a cyclic fashion. Currently used only in BaGM-Sidescan.

The crest length for each sand wave of the short-crested pattern is randomly selected from 1 to 3λ. It is not necessary to include a line for this in the input data file since it happens automatically with the selection of the short-crested option.

The brick pattern sand ripple choice is presently available only in the older versions of ripple#.f, although its inclusion in other versions is planned. This pattern is much more complex than the long and short-crested patterns, but the input parameters are the same, since, so far, the short-crested component has the same parameters as the long-crested component.

Intermediate- and Wavy-long-crested

These sand wave crest patterns have all of the information included above for the long-crested, short-crested, and brick patterns with the following additional line(s).

- Crest length code: applies to intermediate-crested patterns only, determines the range from which the randomly selected crest length is taken. Choices are as follows:
  a. User determined crest length value (set value between 3λ and 8λ). If this option is selected, there is a line immediately following the crest length code with this value.
  b. Crest length, L, for each sand wave is randomly chosen from the range $3\lambda \leq L \leq 5\lambda$.
  c. Crest length, L, for each sand wave is randomly chosen from the range $4.5\lambda \leq L \leq 6.5\lambda$.
  d. Crest length, L, for each sand wave is randomly chosen from the range $6\lambda \leq L \leq 8\lambda$.
  e. Crest length, L, for each sand wave is randomly chosen from the range $3\lambda \leq L \leq 8\lambda$.
- Crest wavelength: applies only to wavy, long-crested pattern, defines the oscillation frequency of the crest pattern. Currently crest wave amplitude is a set fraction of the crest wavelength; eventually, this will be user selected.

Random and Modified Random

- Number of ripples: The number of sand ripples or sand waves that will be included and added. In ripple5.f, the maximum number is 15. In other programs and modules it is not limited.
- Maximum sand wavelength: The largest value for the wavelength of any sand ripple in the set.
- Minimum sand wavelength: The smallest value for the wavelength of any sand ripple in the set.
- Sand wave height: the combined height of all sand waves or ripples in the model. Selected so that $\eta \leq 0.21$ for all sand waves.
- Sand grain size: in mm, not currently used with the model. Applies to sea floor scattering strengths in sonar models.

In the random ripple patterns, for all sand waves or ripples included, the sand wavelengths are randomly selected from between the specified minimum and maximum sand wavelength values. The sand wave amplitudes are then randomly selected subject to the following conditions: i.) $\eta \leq 0.33$ for all sand waves[1]; and ii.) the sum of the sand wave amplitudes is not more than $1.1\times$ the input maximum sand wave height. If necessary, sand wave heights are scaled to meet these requirements. The sand wave orientation with respect to the observation direction is also randomly selected.

There is no provision for sand wave symmetry in the random ripple subroutines. In these cases, the randomly selected sand wave starting point will determine the sand wave symmetry. An option for sand wave symmetry in the random ripple patterns can be added if a situation warrants it.

Cuspate

At present, this sand wave pattern is only available in BaGM-3D. It may be possible to include it in BaGM-Sidescan as well, but the horizontal components of the sand wave pattern make it unlikely that it will ever translate into the format of Standard BaGM.

- Orientation angle, θ: determines the angle of the sand wave with respect to the observation direction. Possible range from 0.00 to 180 degrees. Not presently used in standard BaGM program ripple5.f.
- Sand wavelength, λ_{wave}: user selected, generally should be at least 5 times the step size used.
- Wavelength shift: a value for a random λ_{wave} shift for a sea floor. Takes into consideration the fact that the actual measured λ_{wave} is averaged. Used primarily when averaging scattering results from several sea floors.
- Phase shift, ϕ: determines the sand wave symmetry, also influences the starting point on the sand wave

[1] The choice of $\eta \leq 0.33$ was made in this case so that after the sand waves are scaled there is still a possibility that one or more sand waves can have $\eta \leq 0.21$, the theoretical upper limit.

profile. Entered in degrees, may range from 0 to 360. If $\phi < 180°$, this defaults to $\phi = 90°$, and $\phi \geq 180°$ defaults to $\phi = 270°$ for the maximum possible asymmetry of the sand wave.

- Sand wave height, h: the peak amplitude of the sand wave. Selected values are not limited, but the theoretically and experimentally valid range is from 0.0001 to $0.21\lambda_{wave}$.
- Crest wavelength: $2\times$ the point-to-point distance on a sand wave.
- x-starting point: determines the starting point on the sand wave with respect to λ_{wave}. Negative numbers specify a randomly selected value.
- y-starting point: determines the starting point on the sand wave with respect to λ_{crest}. Negative numbers specify a randomly selected value.
- Sand grain size: in mm, not currently used with the model. Applies to sea floor scattering strengths in sonar models.

Cuspate sand waves/ripples are made by scaling a $\eta = 0.20$ wave height with $C = 0.0$ at the tips of the crest and $C = \frac{h}{0.20\lambda_{wave}}$ at the peaks of the crest. Whether the crests are forward facing or backward facing is determined by ϕ, where $\phi = 90°$ is forward facing and $\phi = 270°$ is backward facing.

Appendix B

BaGM-1D

The "original" set of programs that have become one module of BaGM are named 'ripple#.f', # = none, 2, 2b, 3, 4, and 5. The numbers on the name came about as major changes were made to the program. Rather than risk losing a working version of the model, a new copy with an incremented number was made so that the change could be tested before becoming the new standard. The program is written in FORTRAN77. The current standard for this module of BaGM is 'ripple5.f'.

In addition to writing files containing the range vs sand wave height data, each of the ripple#.f programs writes a summary file, hite#.dat (# = none, 3, 4, and 5). The program ripple5.f differs from the earlier versions of ripple#.f in many ways. Two of the more obvious are in the way that multiple bedforms are handled and in the form of the output data file, hite5.dat.

BaGM-1D (ripple5.f) DATA FILES

Input File: rip5.in

The input data file rip5.in for BaGM-1D includes information about the sonar to be used in the acoustic model as well as region and sand wave parameters. A sample input data file follows:

8	% sonar type code
1	% # of beams (or radials)
2.2000	% beam width/spacing (degrees)
0.1000	% sonar pulse length (s)
65.0000	% total range (m)
1	% number of regions
1	% number of bedforms
65.0000	% max. range of region 1
0.7500	% sand wavelength, bedform 1
1.0000	% sand wave type
0.0750	% sand wave height
0.3750	% phase shift (m)
0.0000	% trough length (m)
1.0000	% scale factor, C
0.0003	% sand grain size
0.0800	% step size for region 1

The sonar information includes the sonar choice which, depending on the selection, may determine the number of radials used, beamwidth, and sonar pulse length. Follows is the section of 'rip5.in' that refers to the sonar type.

```
8        % sonar type code
10       % # of beams (or radials)
```

2.2000	% beam width/spacing (degrees)
0.1000	% sonar pulse length (s)

The first number is the sonar type code. Presently, choices for the sonar type code are:

#	Sonar	# beams	Beam width (deg.)	pulse length (s)
1	----	31	2	1
8	User defined	User defined	$0 \rightarrow \frac{180}{\# \text{beams}}$	
9	NONE	1	N/A	0.01

If the sonar type is other than option 8, "User defined," the following three lines with the number of beams, beam width or spacing, and the sonar pulse length are not included in 'rip5.in' because they are set. Options 8 or 9 are selected for the sonar choice when BaGM is used independent of any specific sonar. Option 8 is used to produce sets of radials or paths to represent a region. The number of paths, their angular spacing, and pulse length are set by the user. Option 9 computes sand wave heights along a single path. The pulse length is set very small so that the minimum program allowed step size can be relatively small.

The number of beams and beam width are used in determining the size of the region and orientation of each radial with respect to the normal of the sand wave crest line. The pulse length is used to determine the minimum acceptable step size for the acoustic model. This value must be at least equal to the pulse length,T, times one half the sound speed in water. For smaller pulse lengths, the minimum pulse length may be longer than this.

Following the sonar parameters is the total range, which is the total length of each radial. This length can be divided into multiple regions, with each region running across all radials. The number of regions is limited only by the number of steps in the data file, although large numbers of regions are not recommended. If the sea floor material changes with each region, then the maximum number of regions that can be used is limited by the acoustic model constraints on the allowed number of sea floor scattering strengths. Transitions between regions can be abrupt; smoothing the transitions between regions is a planned future enhancement. In the sample shown, the total range is 65.0 m, representing a single region. When there is only one region, the maximum range for the region is equal to the total range. For multiple regions, the maximum range of the last region is equal to the total range.

65.0000	% total range (m)
1	% number of regions
1	% number of bedforms
65.0000	% max. range of region 1

In this sample, the region contains only one bedform; however, each region can contain up to 10 overlying bedforms. The more bedforms that are included in a region, the greater the probability that the steepness of the sand wave will exceed the angle of repose, resulting in an unphysical pattern. The user is responsible for guaranteeing that the angle of repose is not exceeded. The number of bedforms used in the input file is the maximum number of bedforms used in any region. For example, if the total range is divided into three regions, one with one bedform, one with three bedforms and the last with two bedforms, the number three is entered for the number of bedforms, with the "extra" bedforms in the regions having only one or two bedforms entered with sand wave heights of zero.

After the maximum range for the first region, the sand wave parameters for all bedforms in the region are listed in sets of parameters. The minimum value for any sand wavelength is five times the region step size, but more steps per wavelength are recommended. The sand grain size and step size for the region are listed last. The sand grain size is not used in the BaGM. Eventually it will be used as BaGM is expanded to include generation of scattering strength files for the acoustic model.

0.7500	% sand wavelength, bedform 1
1.0000	% sand wave type
0.0750	% sand wave height
0.3750	% phase shift (m)
0.0000	% trough length (m)
1.0000	% scale factor, C
0.0003	% sand grain size

After the sand wave data for each bedform in the region are listed, the stepsize for the region is listed. Usually the same stepsize is used for all regions, but that is not necessary.

0.0800	% step size for region 1

The range and sand wave parameters for all successive regions are listed in the same manner.

Output Summary File: hite5.dat

The most recent ripple#.f programs (# = 3, 4, 4b, and 5) generate output files, hite#.dat, where # labels the ripple#.f version. These summary files contain information about the sonar choice, output data file names, and region, bedform, and range parameters. The output data files are created and initially listed under the names "bath3.xx," where "xx" is the radial number. After BaGM has generated the bathymetry, the data files and summary file are saved under an identifying name so that they can be stored and retrieved for analysis.

A sample summary file, hite5.dat (renamed tlcdat.020, indicating tidal long-crested data, run number 20), of the most up-to-date version, ripple5.f, is displayed below. The sonar data are displayed initially. This is important since it identifies the number of data files in the set (equal to the number of angles, 31). Next, the angles and name under which the data file for that angle is stored are listed. This is followed by the number of regions, the number of bedforms per region, and a description and list of parameters for each bedform in each region. In all other hite#.dat files, the region and bedform information is listed before the list of output data files. That was changed in ripple5.f to simplify reading of data file names by the auxiliary program bd5.f

(Please note: the input file above, rip5.in, does not correspond to this output summary file, tlcdat.020.)

Sonar data:

Sonar choice:	----
Beam width:	2.00000
Sonar beam range (deg.):	-30.00- 30.00
Number of angles:	31

Beam angle	File name
-30.00	tlc01.020
-28.00	tlc02.020
-26.00	tlc03.020
-24.00	tlc04.020
-22.00	tlc05.020
-20.00	tlc06.020
-18.00	tlc07.020
-16.00	tlc08.020
-14.00	tlc09.020
-12.00	tlc10.020
-10.00	tlc11.020
-8.00	tlc12.020
-6.00	tlc13.020
-4.00	tlc14.020
-2.00	tlc15.020
0.00	tlc16.020
2.00	tlc17.020
4.00	tlc18.020
6.00	tlc19.020
8.00	tlc20.020
10.00	tlc21.020
12.00	tlc22.020
14.00	tlc23.020
16.00	tlc24.020
18.00	tlc25.020
20.00	tlc26.020
22.00	tlc27.020
24.00	tlc28.020
26.00	tlc29.020
28.00	tlc30.020
30.00	tlc31.020

There is one region.
There are 1 bedforms per region

For bedform 1 sand wave data is:
Bedform type is long crested
Bedform is trochoidal and symmetric

Bedform data:

Wavelength (m):	10.00000
Ripple height (m):	1.00000
Phase shift (deg):	180.00000
Grain size (m):	0.00030
Rnd. phase shift (m):	6.26314
Minimum distance (m):	0.000000
Maximum distance (m):	998.776794
Input max. dist. (m):	1000.000000
Step size (m):	1.251600
Number of steps:	799

Output Data Files: bath3.xx

The data files, bath3.xx, produced by Standard BaGM are relatively simple. There are two columns. The first column is the range in meters, starting from zero and running to the maximum distance. The second column is the calculated sand wave height. The radial information is contained in the data file extension, "xx", where the xx is the two character radial number. After generation by BaGM, the data files are renamed in the structure: aaaaxx.###, where aaaa is an abbreviation indicating the bedform type, xx is the radial number as in the original file name, and ### is a three-digit number indicating the iteration of that type of sand wave.

The following is a sample section from one of the bath3.xx data files. The step size is 1.2516 m, the maximum sand wave height is 1.0 m, and the sand wavelength of the sample is 10 m.

58.8252	0.9603
60.0768	0.9990
61.3284	0.9802
62.5800	0.8215
63.8316	0.3825
65.0832	5.2948e-3
66.3348	0.2550
67.5864	0.7237
68.8380	0.9444
70.0896	0.9969
71.3412	0.9887
72.5928	0.8661
73.8444	0.4714
75.0960	0.0310
76.3476	0.1762
77.5992	0.6587
78.8508	0.9239
80.1024	0.9933

BaGM produces a data file consisting of two columns; the first is the range, the second is the corresponding sand wave height for each radial. The second dimension to the area of the bathymetric representation is produced by constructing a matrix, the columns of which are the modeled heights along each radial extracted from the data files. The range information is stored in an array, since the step sizes are the same for all radials (if this is not the case, the range information is stored in a matrix as well). The bathymetry height matrix is then plotted against the radial number and range for a rectangular plot displaying the sand heights along each radial. A more accurate representation of the area is a polar plot. The two-dimensional aspect of the region comes from interpolating between the radials.

The definitions of the abbreviations, aaaa, are listed below, with the letters used in the abbreviations in boldfaced type:

- **l**ong-**c**rested **ba**thymetry
- **l**ong-**c**rested using the **n**ew or current version of the **b**athymetry equation
- **s**hort-**c**rested using the **n**ew or current version of the bathymetry equation
- **t**idal **l**ong-**c**rested
- **a**symmetric **l**ong-**c**rested
- **w**avy **l**ong-**c**rested

- random

AUXILIARY PROGRAMS: BaGM-1D

ripin5.f

The program ripin5.f writes or edits the input data file, rip5.in, for the standard version of BaGM (ripple5.f). It first searches for an existing input file. When one is found, current input values are displayed. The user then has the option of line editing this file or changing all input values. After completing the edits, the revised input data are again displayed for verification.

This front end program is intended to make using BaGM easy for those unfamiliar with the program. For more experienced users, particularly when only a few input parameters are changed between BaGM runs, it is usually quicker and easier to directly line edit the input data file.

bd#.f

BaGM produces sand wave height above zero, which is defined to be the bottom of the trough. When the bathymetries are used with an acoustic model (or other model), the values must be converted to depth in the water. That is the purpose of the set of programs "bd#.f" (b = bathymetry, d = depth, and # corresponds to the version number of the standard BaGM module). bd#.f reads the '.dat' file generated with the bathymetry files to get the names of the data file(s) created by BaGM. Then the program asks for the maximum range and maximum depth of water. The maximum range is used to adjust the final data point in the output file to satisfy a sonar model requirement that the total range be greater than the maximum range of interest by 3 to 5 times to guarantee that the ray tracing has ended. The sonar model measures water depth from the surface down to the sea floor, so the sand wave/bathymetry height is subtracted from the depth of the water.

The different versions of bd#.f are designed to consider the structure and format of the '.dat' file for each created bedform. The programs are simple and creating multiple versions to format the output data files to fit with other model requirements is not difficult.

BaGM-1D FLOW CHART

Figures B–1 and B–2 contain the flow chart for BaGM-1D, also known as ripple5.f.

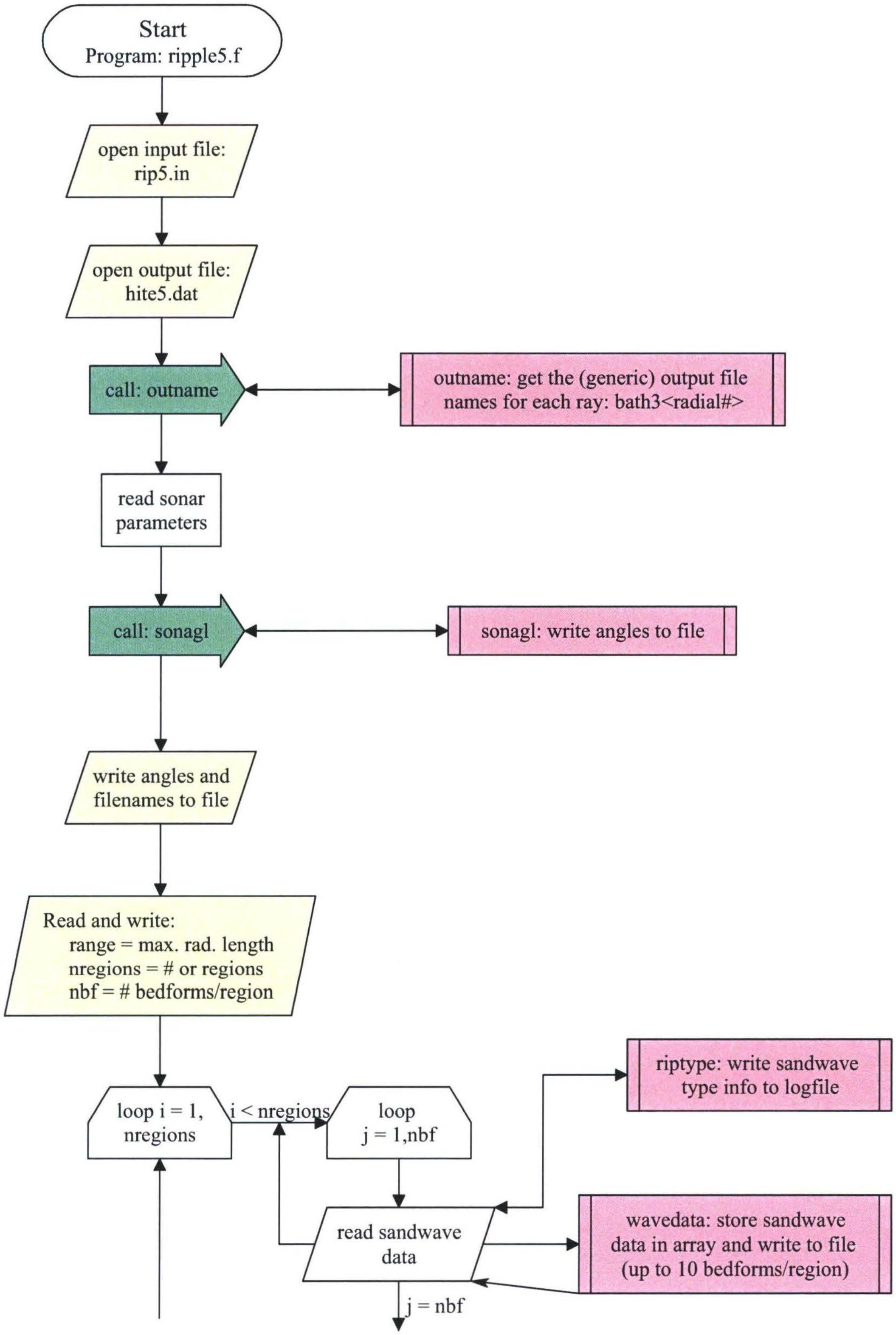


Fig. B–1– BaGM-1D flow chart

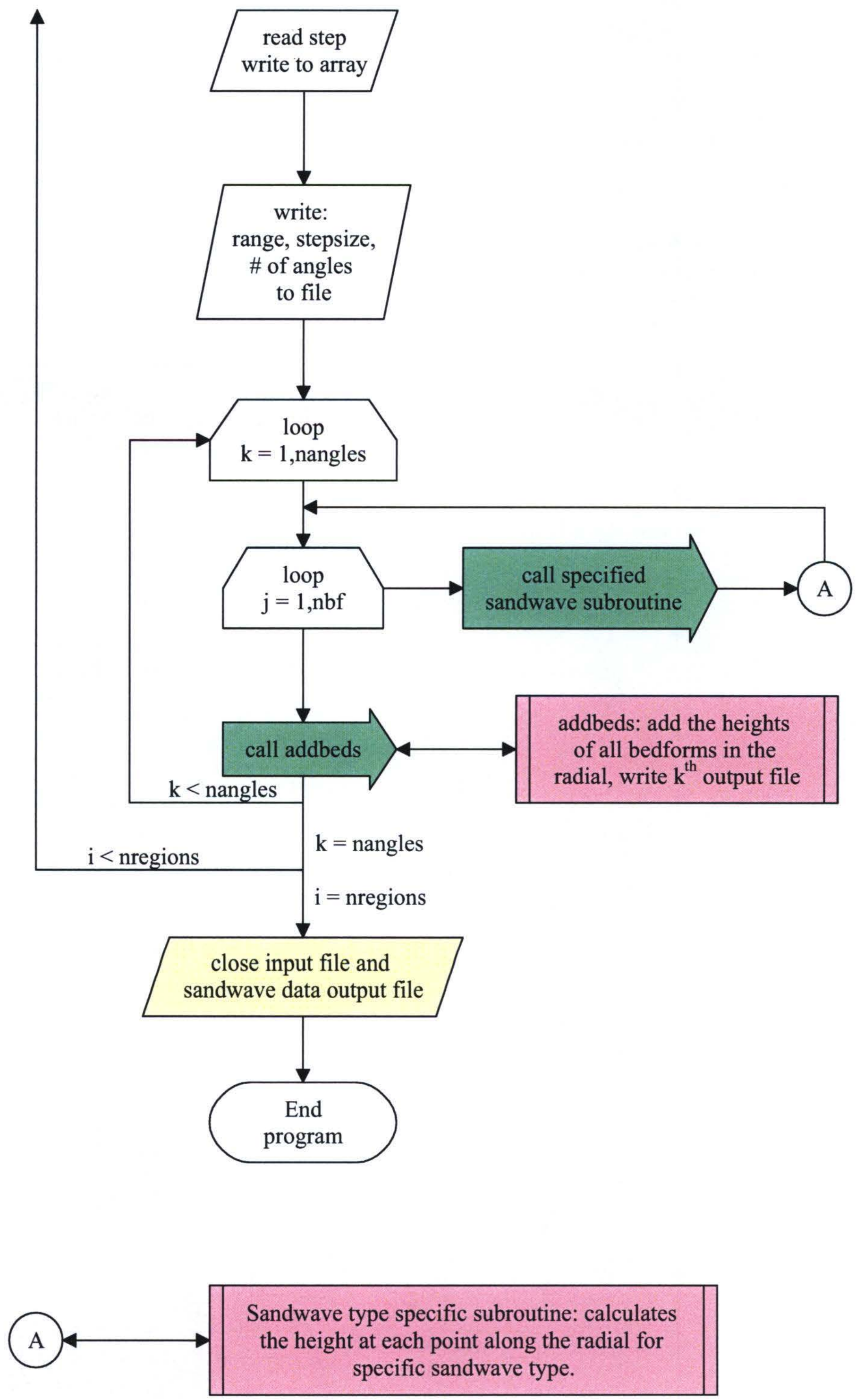


Fig. B–2– BaGM-1D flow chart (continued)

Appendix C

BaGM-SS

The module called BaGM-SS has two versions, sidescan.f and sidescn2.f. As with the BaGM-1D module programs, ripple#.f, the "2" in sidescn2.f indicates a more complex program with additional features available for expanding on the number and types of sea floors that can be represented. BaGM-SS is not as sophisticated as the BaGM-1D module. No sonar information is included in the model. The notation for the number of sonar tracks defines the number of radials in the y-direction that will be calculated. The number of steps in the x- and y-directions are 800 and 500, respectively. There are no theoretical constraints on the number of steps. These values are selected to meet acoustic model requirements for the maximum number of steps in an input file and to place limits on the amount of memory allocated for data storage by the program.

The multiple bedforms per region feature is under construction in sidescn2.f. It is possible that the final structure of the program will differ from the flow chart below to facilitate this feature. This version does have an advantage over BaGM-1D in that it is possible to define regions of different sand wave characteristics in both the x- and the y-directions.

BaGM-SS DATA FILES

Initially sidescan.f and sidescn2.f use the same input file, "scan.in." Now, however, planned and in-progress modifications to the capabilities of "sidescn2.f," including production of an output summary file much like the corresponding file produced by BaGM-1D, multiple bedforms per region, and multiple x-direction regions have necessitated a different input file format. The new input file will be named "scan2.in." The output data files have the same structure as the BaGM-1D data files. The first column is the range, starting from zero and running to the maximum distance. The second column is the calculated sand wave height. In this case, the y-dimension is represented by the individual output data files, with the y-steps numbered sequentially from one to the maximum number of files. When plotting the representation of the sea floor, successive files represent the y-direction steps. The spacing between the steps is determined by the step size, and may be found in either the input file, if saved, or the output summary file.

Input File: scan.in and scan2.in

The scan.in and scan2.in data files begin with information about the number of regions in the y-direction. As yet, this BaGM module is not set up for multiple regions in the x-direction. It then gives the total number of sonar tracks; this is actually the number of y-steps in the region, since there is no requirement that all of the paths produced by BaGM be transferred on to the acoustic model. Next the information about the size of the region of interest and the step sizes in each direction are entered. After the y-step size is entered, the information about the sand waves in each region is entered, starting with the number of sonar tracks or y-steps in that region and ending with the sand grain size.

A sample of the scan.in file follows. Although the overall format is different, there is a great deal of similarity between this file and rip5.in used with the ripple5.f program.

2	number of regions (y)
500	total number of sonar tracks (y steps)
50.0000	maximum dimension in the x-direction
.0800	step size in the x-direction
100.0000	maximum dimension in the y-direction
0.2000	step size in the y-direction
320	number of sonar tracks region 1
1	bedform type (long crested)
0.0000	orientation angle
6.0000	sand wavelength
91.0000	phase shift
0.0000	trough length
0.8500	sand wave height
1.0000	scale factor
.0003	sand grain size
0.0000	number of wavelengths for a change of 2π
180	number of sonar tracks region 2
3	bedform type (random)
5	number of ripples
1.2000	max. sand wavelength
0.5000	min. sand wavelength
0.3000	sand wave height
.0003	sand grain size

The first line in the file is the total number of regions (in the y-direction) in the area to be represented. The second number is the total number of y-steps to be made. This number is equal to the product of the maximum range and step size in the y-direction as well as to the sum of the number of sonar tracks for each region. Following the total number of sonar tracks is the maxium range and step size in the x-direction and y-direction.

Once the maximum values have been entered, the information concerning the individual regions is entered. For each region, this consists of the number of sonar tracks or y-steps for that region and the bedform parameters. In the example above, there are two regions, the first nearly twice the size of the second. If the input file in the example above had been scan2.in, there would be a line following the number of sonar tracks for each region giving the number of bedforms per region.

The bedform parameters are then entered as in the rip5.in data file. For a long-crested sand wave pattern, in addition to the sand wave parameters available in the rip5.in file, there is an additional line for the "number of wavelengths for a change of 2π." This line is used if the symmetry of the sand wave is variable over the region at some predetermined length scale. It is set equal to zero if the symmetry is not variable.

BaGM-SS FLOW CHART

Figure C–1 is the flow chart of BaGM-SS as it currently stands. The primary difference between this iteration of the module as compared to the original program module, the flow chart of which is shown in Fig. C–2 is the automation of the naming of the output files and the possibility of multiple overlying seafloors in the final output file.

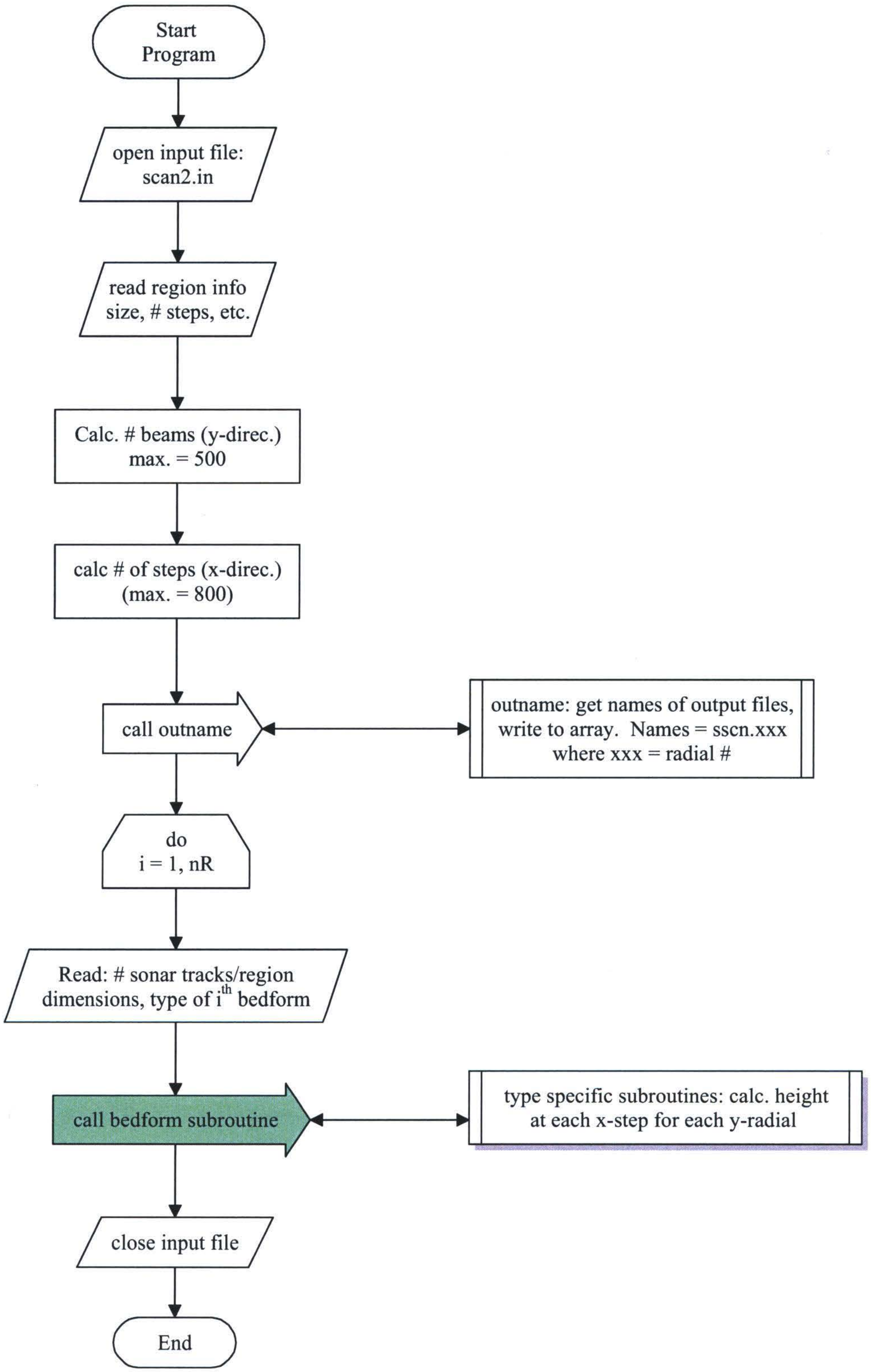


Fig. C–1– BaGM-SS flow chart

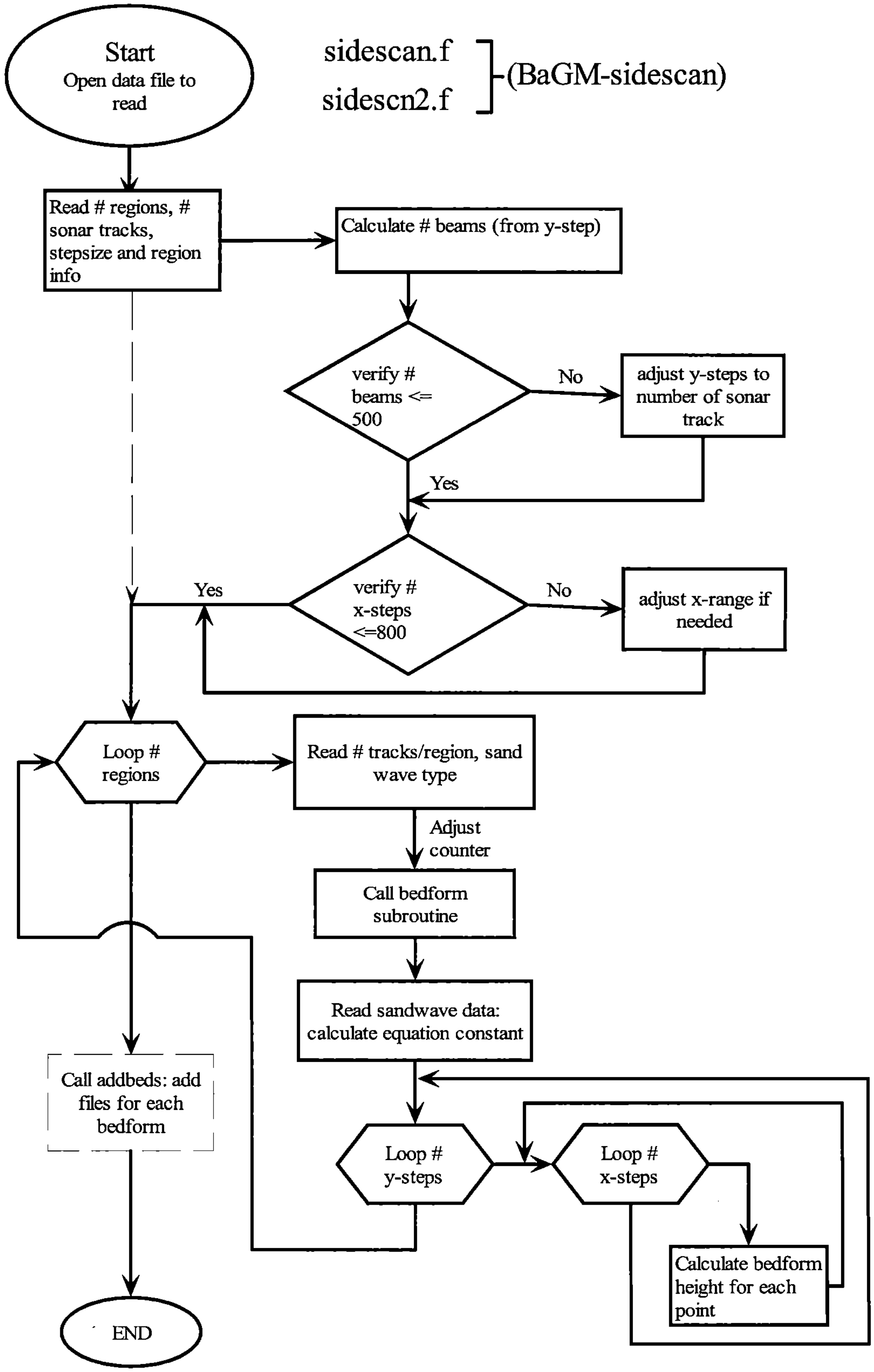


Fig. C–2– Original BaGM-SS flow chart

Appendix D

BaGM-3D

BaGM-3D is optimized for producing very detailed representations of small patches, however, it can be used with any size region. In the version "wedge.f," the grid spacings in the x- and y-directions are equal. In "wedge2.f" and "wedge3.f" the grid spacings for the two coordinates are independently set, with "wedge3.f" the default version of BaGM-3D. In these three versions, the patch considered is assumed to be very small, therefore multiple regions, i.e., areas of differing sandwave pattern or sea floor material, are not allowed. A fourth BaGM-3D version, "wedge4.f" is patterned off "wedge3.f" and includes a subroutine that varies the sandwave scale factor so that multiple regions may be defined. Up to three overlying bedforms are allowed in wedge.f and wedge2.f. Neither wedge3.f nor wedge4.f allow multiple overlying bedforms in the original data file; however, an auxiliary program, 'addfile.f' adds bedform files created in wedge3.f or wedge4.f to form the multiple bedform patterns. Addfile.f was separated from wedge3/4.f so that the individual components of multicomponent sea floors could be analyzed and/or evaluated separately to determine the major source of scatter for the combined set. Wedge3/4.f also includes an option for a random shift or user determined in starting position, δ, as described in Section 2, in both the x- and y-directions. One advantage to creating each sea floor component separately is that as many components as are wished may be added.

BaGM-3D INPUT FILE

The input data file for BaGM-3D, wedgeX.in (where X = 2, 3, 4), starts out with information about the total region, the number of bedforms, the dimensions and step sizes in the x- and y- directions. Then the information about the individual bedforms is included sequentially, starting with the bedform type and ending with the sand grain size for each bedform.

A sample input file follows.

	2	number of bedforms
*	2048	number of steps in the x-direction
	.0018	step size in the x-direction
*	1024	number of steps in the y-direction
	.02	step size in the y-direction
#	ssl.453	bedform name
	1	bedform type (long crested)
	20.	orientation angle
	5.0	sand wavelength
**	0.1	decimal variation in wavelength
	90.	phase shift
	0.0	trough length
	.51	sand wave height, h

	1.00	scale factor (negative scale factor implies variable, wedge4.f only)
**	-1.	starting point (long crested only, negative implies random)
**	1	select equation (1 = scales from -h/2 to h/2; 2 = scales from 0 to h)
	.0003	sand grain size
#	fds.078	sandwave name
	3	bedform type (random)
	7	number of overlying ripples
	.12	maximum sand wavelength
	0.07	minimum sand wavelength
	0.032	maximum combined sand wave height
	.0003	sand grain size

* In wedge2.f, this would be the "maximum distance in the x/y-direction"

Not used in wedge2.f. All bedforms created at a time in wedge2.f are added in the program so given a single name

** Used in wedge4.f only

AUXILIARY PROGRAMS

addfile.f

Based on the subroutine 'addfiles' used in other BaGM modules and programs, this is an auxiliary program to wedge3.f. This program will add, point-by-point, the respective sand wave heights from up to five individual sea floors. It is the responsibility of the user to make sure that all sea floors in the added set have the same number of points and the same x- and y-grid spacing. As a subroutine, this program added the sea floors when created, with the final result the combination sea floor. The advantage of a standalone program is that the composite sea floor parts are easily broken down. This makes obtaining scattering results for the individual components as well as the composite sea floor possible. In this way, the dominant features of the composite sea floor can be identified.

rough.f

The programs rough.f and rough2.f are actually a standalone programs written to test patch shape effects on acoustic backscatter calculation from simulated sea floors used with a scattering strength prediction program. Their output is in the same format as BaGM-3D output. Plus, their results can and have been co-added with BaGM-3D sea floors using addfile.f described above.

The output is a random noise height pattern that should produce the same scattering response regardless of observation direction. Therefore, any variation in the scattering strength with respect to observation direction is directly attributable to the patch shape. These results can then be used to correct the response from the more realistic simulated bathymetry patches for the simulation patch shape effects.

The input parameters for this program are the number of files, the number of points and the grid spacing in both the x- and y- directions, the output file name, sea floor material angle of repose, and the maximum height. Successive points are randomly selected between 0.0 and the input maximum height, subject to the constraint that the angle of repose is not violated for any previously selected point. The constraints on the program do impose a maximum on the ratio of the maximum height and the grid spacing, since they introduce a diagonal bias if the height is too great.

mkapluw.f

This program writes the sea floor material parameter files to go with modeled sea floor regions having different sea floor materials or different effective scattering strengths for the same sea floor material. These files use the APL-UW bottom type parameters. The regions are based on the regions as defined in the 'wedge4.f' subroutines 'scscale' and 'lcscale.'

ssconv.f

This program converts files from the wedge format to the sidescan format. The new "sea floor" can be constructed with a grid density equal to any multiple of the grid density of the original sea floor. The program is currently set up to automatically include a "water depth" in the output file as per acoustic model requirements, but this can be easily modified. To use this program with BaGM-cmb, set the water depth to zero.

BaGM-3D FLOW CHART

Figure D–1 is the flow chart for BaGM-3D in it's current version.

Each sand wave pattern has different characteristics that are read into the sand wave subroutine(s). Consequently, each sand wave type-specific subroutine is different from the others to a lesser or greater degree. However, they all follow the basic outline as shown in Fig. D–2. There are other subroutines called by the sand wave subroutines; these are not shown as they simply consolidate some of the processes. In wedge4.f, for long-crested and short-crested sand waves (to be extended to others), the prior to the calculation of the bedform height, the scale factor that modifies the height is adjusted through the subroutines lcscale and scscale, respectively.

Figure D–3 is the flow chart for the original version of BaGM-3D. This version implemented 'addfiles.f' as a subroutine; this make experimenting with the acoustic effects of very small variations in the bedform, such as small ripples of different types on a single larger bedform very difficult. Therefore, the updated versions use 'addfiles' as a supplementary program.

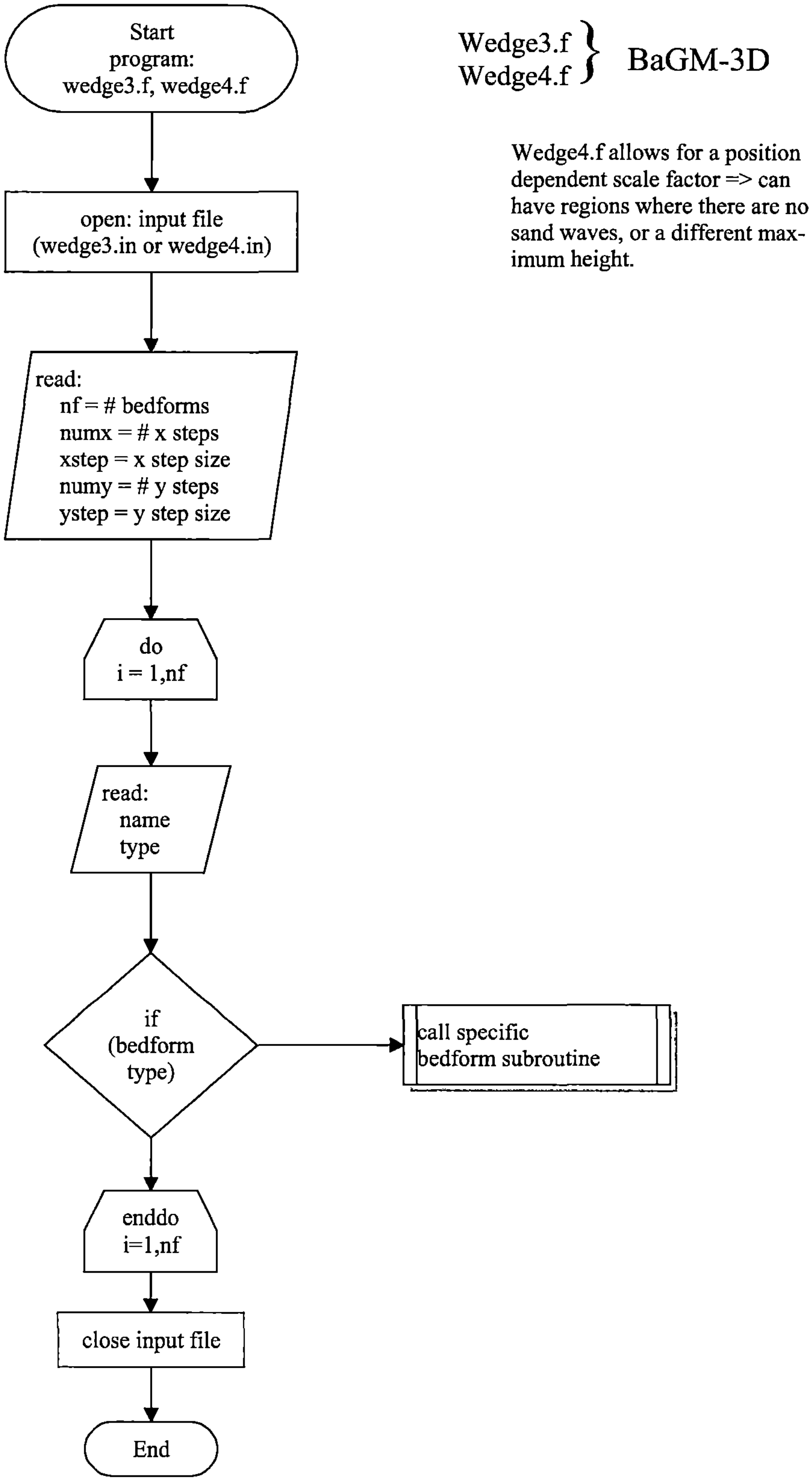


Fig. D–1– BaGM-3D flow chart

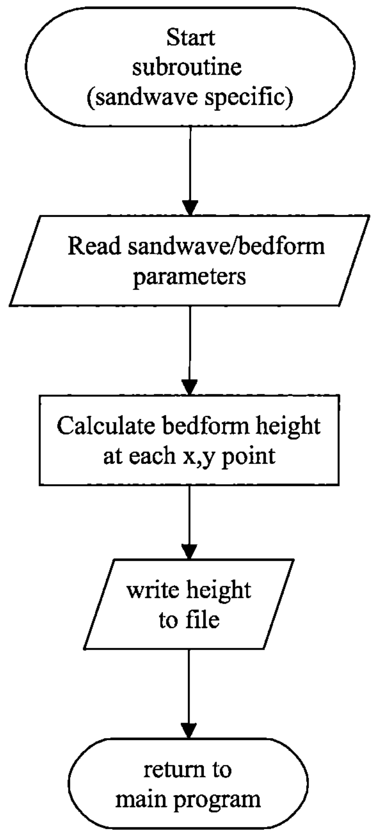


Fig. D–2– Sample sand wave subroutine

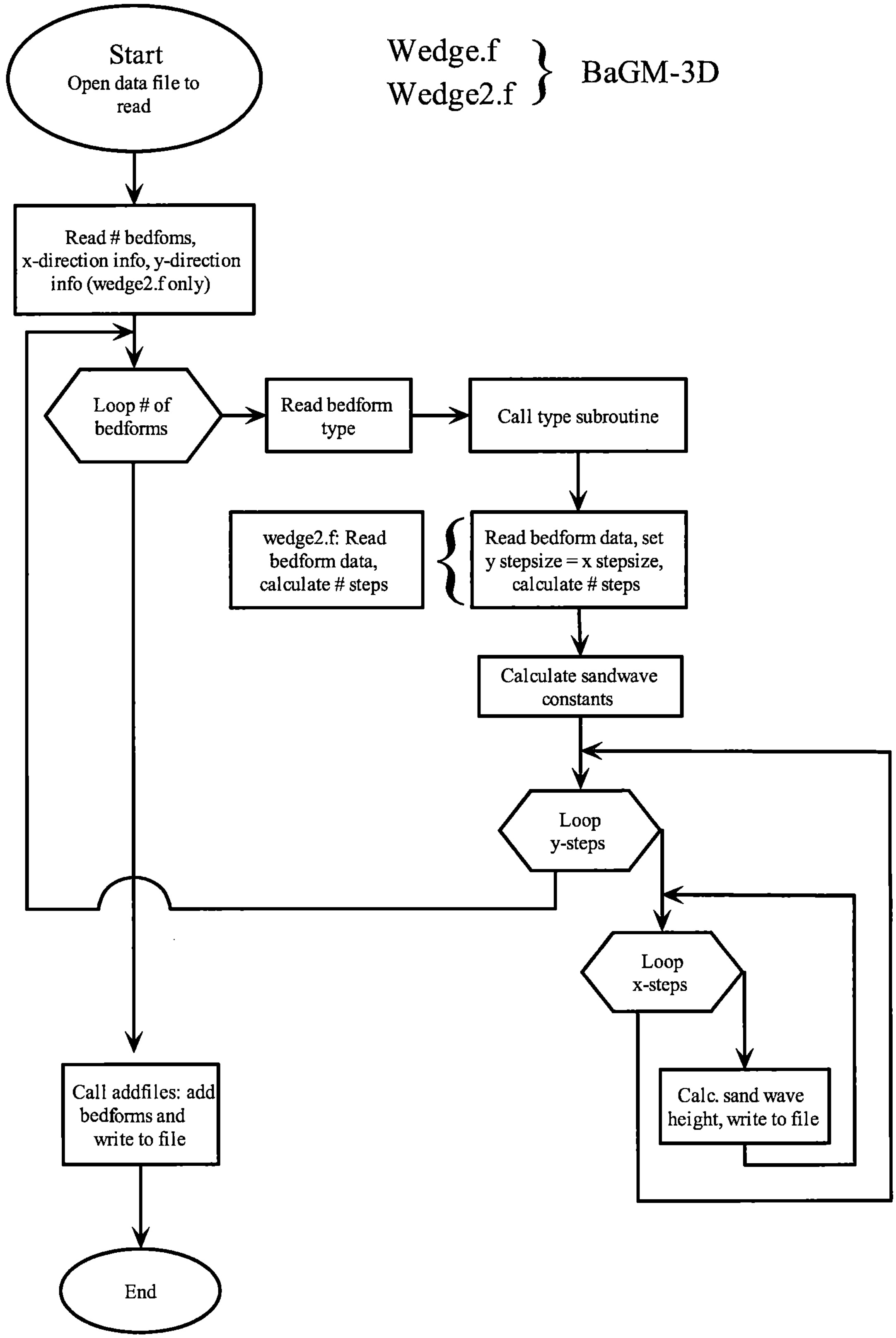


Fig. D–3– Original BaGM-3D flow chart:

Appendix E

BaGM-cmb

The module BaGM-cmb is, or will be, the basis for the full-blown combination model that is in progress. The full model will start with very complex sea floors based on 'wedge4.f'. BaGM-3D, a.k.a. 'wedge4.f,' makes it possible to have sea floors with complex combinations of sandwave patterns, varying materials in different patches, slopes, and, eventually, random or solitary objects. These sea floors can then be broken down into high density individual radials in the BaGM-SS style that is used by BaGM-cmp (using ssconv.f).

BaGM-cmb starts with a BaGM-SS sea floor, from which it extracts BaGM-1D and/or BaGM-SS radials having a different grid density. Figures E–1 and E–2 show the flow chart of the (projected) complete model. At the time of this writing, not all subroutines and functions in the model are fully operational. The finished model will have four actions, which can be done separately or in combination with others. The four actions are: 1) add a solitary object to the sea floor (subroutine still in progress, not operational); 2) make/extract BaGM-1D radials; 3) make/extract BaGM-SS radials; and 4) make the APL-UW sea floor material files for use with acoustic models (subroutine still in progress, for use only with options 2 and 3). It is possible that the program flow chart will have to be modified slightly once the program is completed.

The final form of the output files from the options 2 and 3 listed above is identical to those of BaGM-1D and BaGM-SS, consequently, all the auxiliary programs used with these programs will also work with BaGM-cmb.

For this program, an input file is optional, and the information may also be entered manually. After the range (total distance in the x direction), the step size in the x-direction, the number of radials (number of steps in the y-direction) and the spacing between the radials are entered, the rest of the information is option choice dependent.

INPUT FILE FORMAT

For this program, an input file is optional, and the information may also be entered manually. After the range (total distance in the x direction), the step size in the x-direction, the number of radials (number of steps in the y-direction) and the spacing between the radials are entered, the rest of the information is option choice dependent. There are currently thirteen options, which represent the four possible actions of the model or combinations thereof. These are listed in Table . At the time of this writing, only options 2, 3, and 11 are fully operational. If an option includes action/option #1, then the user must also enter how many solitary objects to input and if they are the same or different. To simply bookkeeping, the model allows for the user to enter the output file names.

AUXILIARY PROGRAMS

ssconv.f

A program to convert BaGM-3D files into several to many 1D, parallel data files in the BaGM-SS style. The 3D nature of the program(s) wedge3/4.f makes representation of a wide variety of sand waves and sea

Table E–1– Possible Actions and Combinations of Actions for BaGM-cmb

Option #	What it does
1	Add solitary or isloated objects or features
2	Extract sonar paths in the BaGM-1D format
3	Extract sonar paths in the BaGM-SS format
4	#1 and #3
5	#1, #3, and #13
6	#1, #2, and #3
7	#1 and #2
8	#1, #2, and #13
9	#1, #2, #3, and #13
10	#2 and #13
11	#2 and #3
12	#3 and #13
13	Make the UAIM seafloor material files

floor combinations much easier than either of the 1D BaGM modules. This program, along with BaGM-cmb, lends that flexibility to the 1D modules (although there is no doubt that some information contained in the original sea floor is inevitably lost by the conversion).

mkapluw.f

This program, like ssconv.f above, also noted as an auxilliary program to BaGM-3D, writes the sea floor material parameter files to go with modeled sea floor regions having different sea floor materials or different effective scattering strengths for the same sea floor material. These files utilize the APL-UW bottom type parameters. The regions are based on the regions as defined in the 'wedge4.f' subroutines 'scscale' and 'lcscale.' Although usable, at present this program is very rough, requiring considerable user input.

BaGM-cmb FLOW CHART

Figures E–1 and E–2 are the flow chart for BaGM-cmb in its present form. As the model is still being developed, the final form could deviate from this flow chart in various ways. Figure E–3 shows the basic structure of the unfinished subroutine 'soliobj' which will insert solitary or isolated objects into the a sand wave field. The algorithm outlined in Figs. E–4 and E–5 is for the BaGM-cmb subroutine 'makebagm1d,' however, it also applies to 'makebagmss' with only minor modifications due to the different area specifications of the two modules.

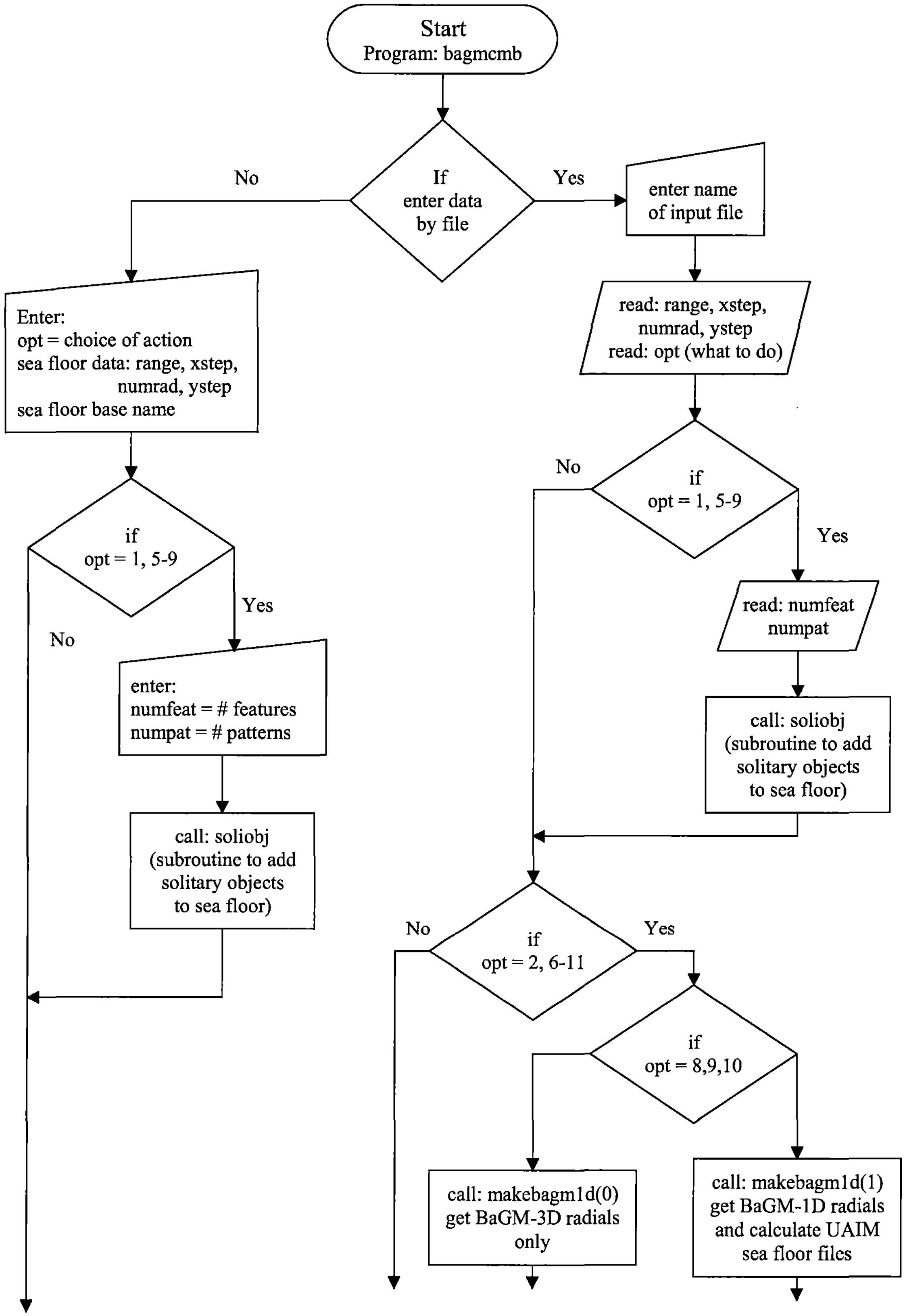


Fig. E–1– BaGM-cmb flow chart

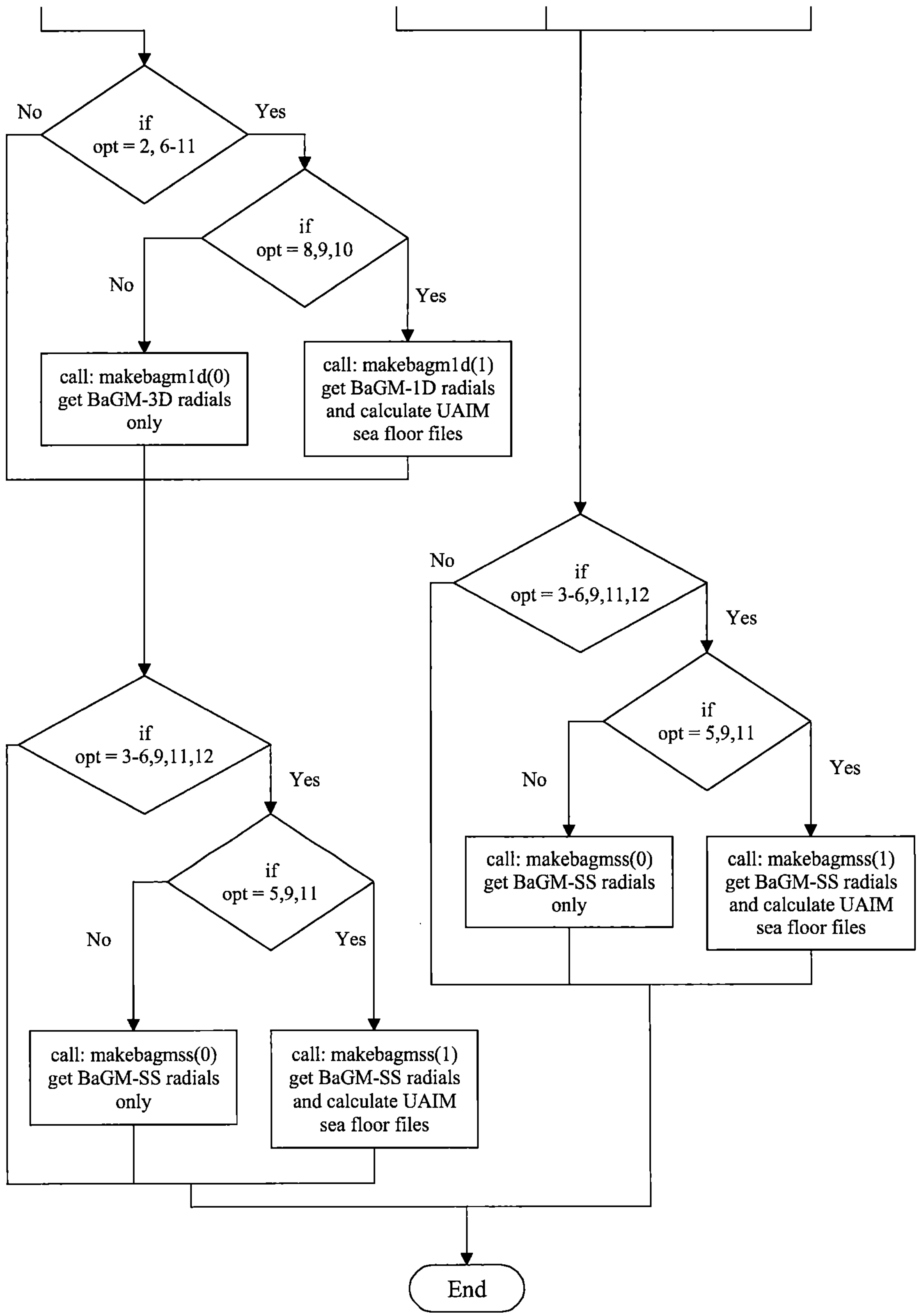


Fig. E–2– BaGM-cmb flow chart (continued)

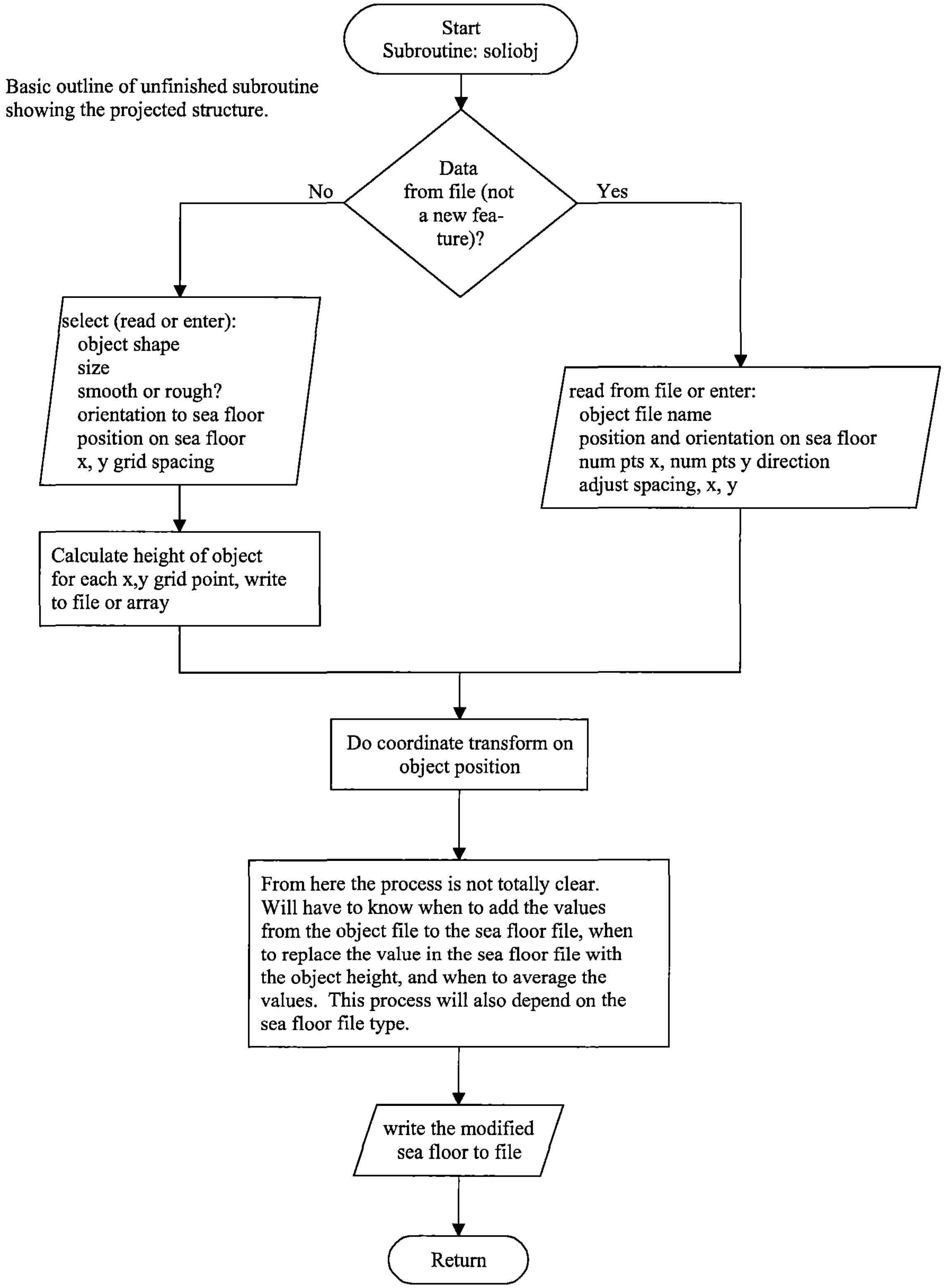


Fig. E–3– Tentative flow chart of the unfinished BaGM-cmb subroutine soliobj

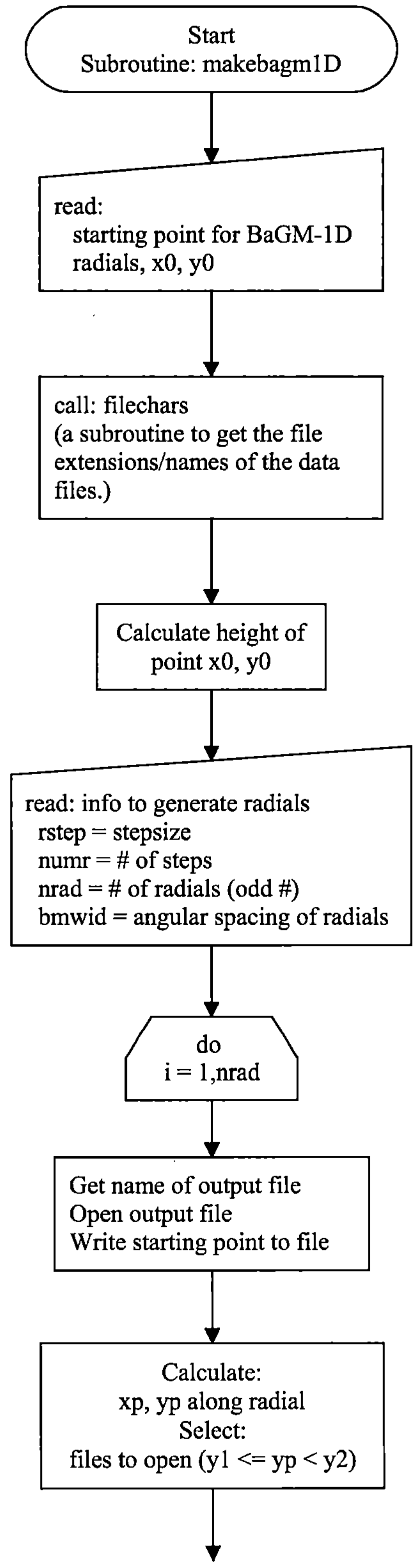


Fig. E-4- BaGM-cmb subroutine makebagm1D flow chart

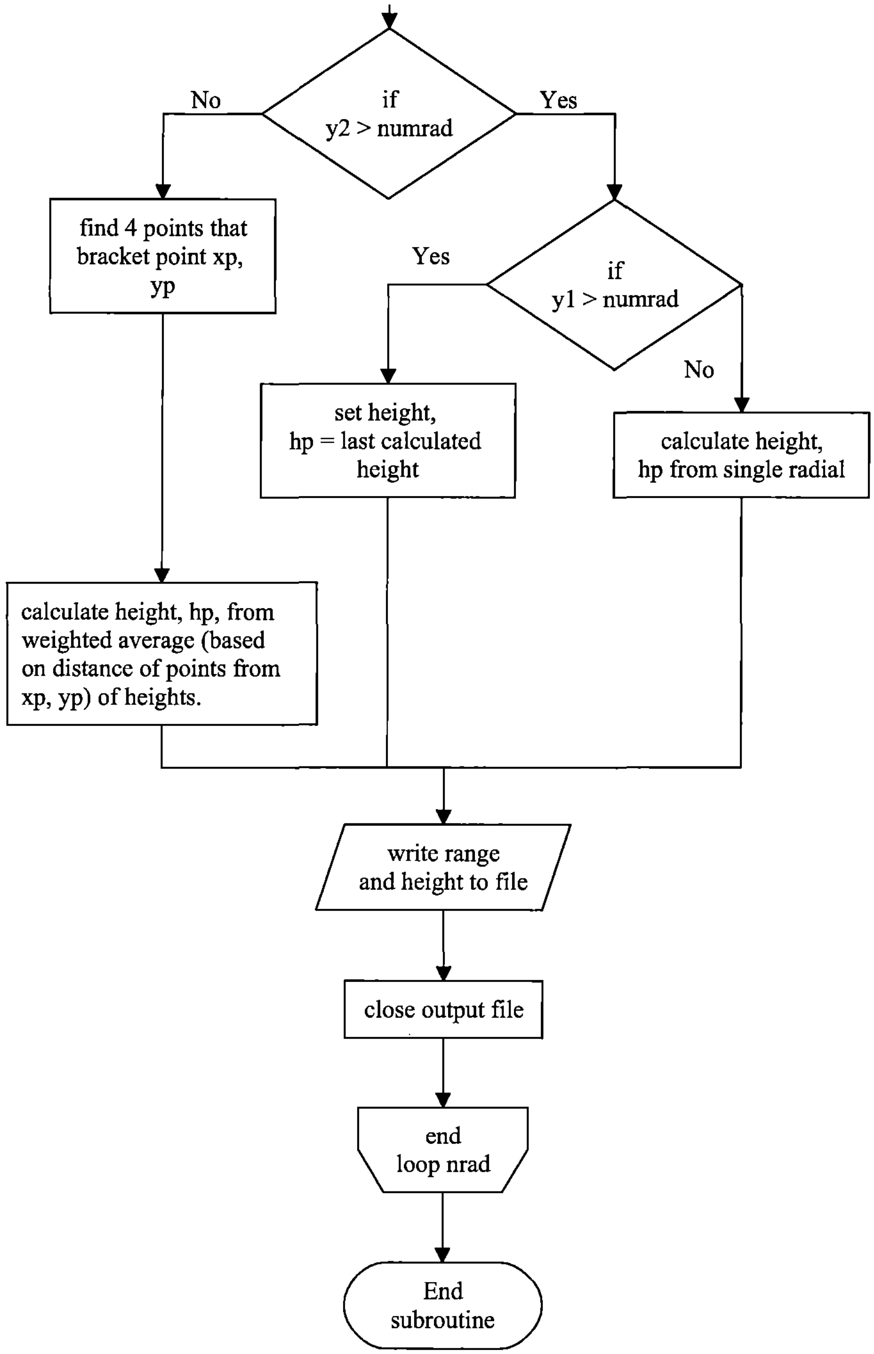


Fig. E–5– BaGM-cmb subroutine makebagm1D flow chart (continued)